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Characterization of shear behaviour in consolidated granular biomass☆

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ABSTRACT

A new vane shear tester is proposed for the determination of the shear strength in consolidated samples of granular biomass. Measurements are performed using forest woodchips with a normal pressure in the range 5–30 kPa applied at rotation rates of 3–13 rpm. The maximum torque is found to be affected by the normal pressure and time of compression. The rotation speed is not found to have a significant influence on the shear strength. The new apparatus is an efficient tool for determining the mechanical characteristics of granular biomass. The results are in general agreement with those given by the standard Jenike method, but the new technique makes testing easier and faster. Quantitative differences between the results obtained using the two methods are possibly a result of the different modes of load application and the geometry of the shear surface.

1. Introduction

As a renewable source of energy, biomass is widely used in the form of woodchips, shavings, and sawdust or in the processed form of briquettes or pellets. Wood biomass fuels are composed of particles of varying size and shape, and exhibit much greater elongation than other agro-granular materials. Knowledge of the mechanical properties of granular biomass is important for the design and efficient operation of equipment for handling, storing, and processing such materials [1–8]. The use of inappropriate material parameters in the design of handling and storage equipment may result in material loss, biomass degradation, and flow stops, which in consequence increase operational costs and may result in equipment failures. Characteristics such as density and parameters of strength, elasticity, flowability, and friction are of particular interest in the bioenergy market. Those strength properties standardized in design codes (such as Eurocode 1 [9]) are necessary for the design of storage facilities and handling appliances. The parameters allow for estimates of the pressures exerted on storage structures by granular materials and ensure reliable flow. In the majority of cases, methods for determining the mechanical properties of biomass are adopted from earlier contributions in the fields of geotechnics and soil mechanics. Usually, these standard methods and apparatus require resizing and redesign to properly treat larger biomass particles. Recently, attempts have been undertaken to establish standard set of techniques for determining the characteristics and parameters of granular biomass. These methods should be simple and quick.

The quality of granular biomass sometimes determines its commercial value; thus, apart from handling and processing, quality control is an important task for the market. The results of tests using standard apparatus should be precise and repeatable, and the tests themselves should be relatively fast. The construction of such testers should be simple and compact, allowing easy transport to appropriate locations. Despite a search for new methods, a lot of granular biomass testing is still conducted using a standard Jenike shear tester or other established apparatus for testing granular materials or powders. Barletta et al. [10] conducted a research project across four laboratories to characterize biomass. The project identified some mechanical properties of granular biomass and indicated some critical requirements for biomass characterization procedures. Gil et al. [4] measured the friction and flowability of woody and herbaceous biomass under various moisture contents in a shear tester following standard procedures (ASTM D6128-06 [11]). Crawford et al. [12,13] studied the effect of physical and chemical pre-processing on the flowability of different kinds of biomass using the FT4 Powder Rheometer (Freeman Technology, Worcestershire, UK) [14,15] and Jenike shear tester [16]. Zulfigar et al. [2] determined the flow properties of biomass and coal blends in a Jenike shear tester with a 95.3-mm diameter cell. The flow properties were found to be dependent on the form of biomass and its blends. Adapa et al. [17] used the Wykeham Farrance apparatus (Wykeaham Farrance International Ltd., Slough, UK) to perform shear experiments on ground agricultural biomass. The apparatus was equipped with a square 100-mm shear box, a force transducer to record the shear force, and a displacement transducer. The authors tested materials under normal pressures varying from 9.8–39.2 kPa. Stasiak

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et al. [18] characterized sawdust and woodchips in terms of their strength properties, flowability, and friction coefficients against popular construction materials using a direct shear tester with a 210-mm diameter shear box. Experiments were performed under different moisture contents and normal pressures of 20–60 kPa. The same authors used a Jenike shear tester of 60-mm diameter [19] to measure the mechanical properties of rapeseed cake and its mixtures with wheat meal obtained under various extrusion conditions. Larsson [20] used a Schulze Ring Shear Tester (Dr. Ing. Dietmar Schulze Schuttgutmesstechnik, Wolfenbuttel, Germany) to measure the friction properties of reed canary grass under low normal pressures (up to 7.5 Pa) and a powder friction measuring device proposed by Solimanjad [21] for high normal pressures (up to 275 MPa). The Schulze Ring Shear Tester has a shear cell with an annular sample slit of area 1.38 cm^2 and volume 1.4 cm^3. The Ring Shear tester was also used by Miccio et al. [22] to determine the flow properties of particulate biomass. Przywara et al. [23] determined the influence of moisture content on mechanical characteristics using a 60-mm diameter Jenike shear tester. Przywara et al. [24] used a rheometer to investigate the influence of moisture content on different kinds of sawdust and coal blends. The design of their equipment was similar to the Ring Shear Tester for determining the shear strength. The ring of the apparatus was 12 mm deep with 102-mm outer diameter and 88-mm inner diameter. The rotation speed of the lid varied from 5 to 300 rpm. Barletta and Poletto [25] determined the flow properties of woody biomass with different moisture contents using the Schulze Ring Shear Tester. Wu et al. [8] measured the mechanical properties of wood pellets, torrified pellets, and woodchips with a large-scale annular shear tester following the procedure of Jenike [16].

In the case of granular materials with complex shapes, determining the angle of repose of biomass is often used in the characterization process. Ileleji and Zhou [26] measured the angle of repose of bulk corn stover with different particle sizes and two moisture contents. The authors used three different measurement methods and stated that the method of determining the angle of repose had no effect on the measured values. However, the angle of repose was found to be influenced by moisture content and particle dimension. Wu et al. [8] determined the angle of repose of three types of solid biomass fuels (wood pellets, woodchips, and torrified pellets) using simple apparatus.

According to Barletta and Poletto [25], assessing the properties of particulate biomass requires further studies and new measuring techniques. The standard methods for characterizing granular materials are not always applicable to particulate biomass. Barletta and Poletto [25] conducted discharge experiments on dry and moist sawdust samples in a plane silo with a total volume of about 0.3 m^3 in which the hopper inclination and outlet width varied independently. In turn, Miccio et al. [22] used the original arching tester to estimate the arch formation in biomass delivered from three different sources.

The vane shear test is widely used to determine the mechanical parameters of a wide range of materials. The method allows for a simple and quick determination of shear characteristics in various food, building, and soil materials. There are also examples of application of such equipment to determine powder and granular parameters. US Patent 4.181.023 [27] describes apparatus for short-duration testing of the flowability of rubber powder. The four-blade vane shearing tool embedded in a cylindrical consolidated sample is used to determine the torque during rotation. The measurement is performed immediately after filling the chamber and after 24 h of compression, and the ratio of these values characterizes the flowability. The vane rheological test was also used by Barois-Cazanave et al. [28] and Daniel et al. [29] to determine the properties of a loose bed of glass beads and coarse granular powder. Samaniuk et al. [30,31] used a vane rheometer to measure the rheological properties of concentrated lignocellulosic biomass and the yield pressure of samples of corn stover and switchgrass. A four-blade rheometer was proposed by Bouillard et al. [36] to characterize powders and nanopowders at low and high shear pressures.

The rotating vane method is widely used in rheology for determining material properties [28]. Barnes and Nguyen [32] reviewed the literature regarding technologies where the vane test had been used and gave a series of examples of its use for various materials. There is little information in the literature on the use of this method for determining the characteristics and parameters of raw granular biomass such as woodchips. The test seems to be a useful tool for determining the properties of biomass for handling and storage. The objective of this study was to construct a vane shear tester (VST) and examine its applicability for samples of forest woodchips consolidated under normal pressures encountered in the storage silos used by power and heat plants. The measurements provide information regarding the load on equipment such as screw conveyors used for emptying the silos. The measured torque values allow estimates of the necessary strength of the construction materials used in transport equipment. The vane shear tester proposed in this project could be useful tool for fast estimation of shear resistance of wood biomass for comparison of different lots of material delivered for storage or processing. The tool should give quick answer whether delivered material substantially fulfills requirements ensuring safety of handling. The maximal torque value could give information regarding strength of the stored granular biomass.

The new vane shear tester, strictly based on construction of rheometer with additional consolidation device, provides measurements in rotating plane in unlimited shear path which is the main disadvantage of the Jenike tester. The second disadvantage of Jenike method is a long term experiment as well as required skills and experience to proper analysis of data from the staff. The time of measurement and required skills of the operator when a vane shear tester is used are markedly reduced.

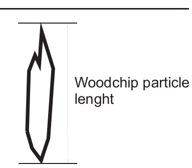
2. Material and method

Experiments were performed on forest woodchips, which is a type of granular biomass widely used in firing and co-firing power and heat plants. The lengths of the woodchip particles were measured with a slide calliper. The particle length distribution and photo of the tested material are presented in Table 1.

Table 1
Forest woodchips used as experimental material.

Forest woodchips
6% m.c.

Particle size (mm)	(%)
>70	1.9
30–70	8.4
16–30	18.3
8–16	23.3
3–8	33.8
<3	14.3



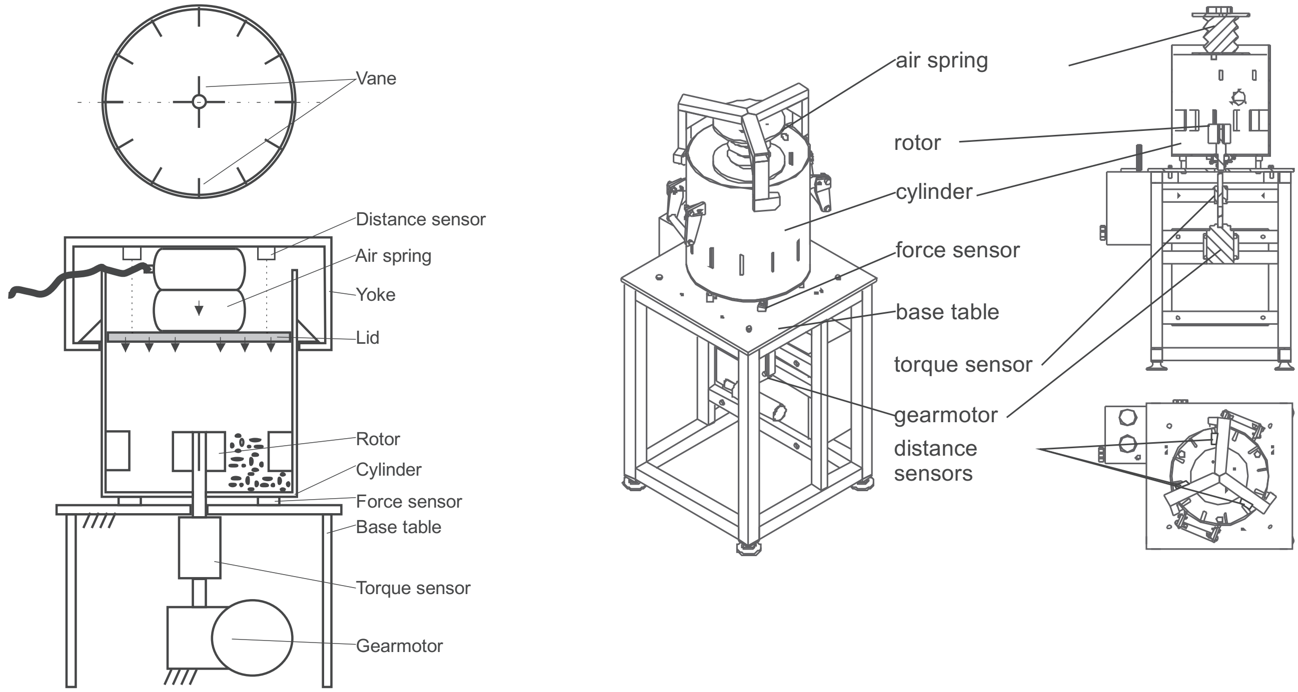


Fig. 1. The biomass vane shear tester VST.

After being delivered, the material was dried in a thin layer in laboratory conditions and its moisture content was determined. Distilled water was then added and the samples were mixed for 15 min of each hour over a 24-h period using a laboratory mixer to obtain the required levels of moisture contents: 10, 20, 30, 40, and 50%. The moisture contents corresponded to those existing in technological practice where biomass subjected to various weather conditions is delivered. Miccio et al. [22] examined wood biomass in a similar range of moisture contents (10–55%). Nystrom and Dahlquist [37] reported that variations in the moisture content of granular biomass from 10 to 64% resulted in serious transport and storage problems. The moisture content was measured by weighing 200–300 g samples before and after 24 h drying in a laboratory oven at 105 °C.

The new VST was designed and built as shown in Fig. 1. The apparatus is equipped with a cylindrical chamber of 40 cm diameter and 40 cm height. Inside the chamber, a rotating vane tool (8 cm high and 12 cm wide) with four blades is located near the bottom. The tool is driven by a gear motor with an adjustable rotation rate. The normal pressure is exerted by a pneumatic system with a rubber air spring and a yoke. The rotating vane impeller is assumed to shear only the material remaining in the immediate vicinity of the blades. On the internal surface of the chamber, there are twelve blades of the same dimensions as those of the rotating tool. The test chamber was placed on a base table and connected to the drivetrain by a claw clutch. The concept of the proposed device is based on a combination of the rheometer and a new system of vertical loading with compressed air filling a rubber air spring and the yoke. The mass of the sample was measured with three load cells supporting the chamber. The actual height of the sample was measured with three laser sensors to determine the density of granular biomass. A torque sensor was used to measure the shear load on the rotating vane tool. Tests were conducted for four rotation rates (3, 6, 9, and 13 rpm) under four levels of normal pressure (5, 10, 20, and 30 kPa). The required normal pressure was generated by the compressor and measured with analogue and digital manometers. The value of normal pressure in the measuring chamber was calculated considering different diameter of the action surface of the air spring and surface of the lid. The influence of the compression time on the torque was also determined. In this case, the sample remained under normal pressures of 5 kPa and 30 kPa for 4 h, and was then sheared with minimum and maximum speeds of 3 rpm and 13 rpm, respectively. The torque vs. time characteristics and other measured parameters were recorded by the data acquisition system.

Weighed portions of biomass were poured into the chamber and consolidated at the prescribed normal pressure. Next, vane rotation commenced at a constant speed. After the torque reached its maximum or asymptotic value, the impeller was stopped. The rotation was stopped after ten decreasing values were measured that followed maximum torque. After a rest period of approximately 50 s, the torque decreased to the asymptotic value. Next, the sample was unloaded and the chamber was emptied. The influence of 4-h compression was examined for normal pressures of 5 kPa and 30 kPa and for two rotation speeds of 3 rpm and 13 rpm.

To compare the results given by the proposed VST with those of the standard method, the strength and flowability were determined using a 210 mm diameter and 100 mm high direct shear tester (Jenike box). The diameter of direct shear apparatus for estimation of material strength parameters should be at last 20 times the maximum particle size (>70 mm according to Table 1) and not <40 times the mean particle size, and the height should be between 0.3 and 0.4D to obtain defined shear plane [18]. The direct shear tester was used for the same material to estimate usability of the new tester. To fulfill recommendation of design code (Eurocode 1), the tester 1.4 m in diameter should be used; however, such a large apparatus was unavailable. To assure required normal load at large area construction of such apparatus would involve large investment. Therefore relatively large (210 mm in diameter) Jenike tester available in our lab was used. The tests followed the Eurocode 1 [9] procedure for normal pressures of 15 kPa and 30 kPa and a shearing speed V of 0.17 mm·s^{-1}. The seemingly high normal pressure used in our testing corresponds to the loads exerted in storage silos by biomass deposits of approximately 10 m, which are typical in practical storage conditions, e.g. in energy plants. Based on the shear force vs. displacement experimental curves, the angle of internal friction, effective angle of internal friction, flowability index, and cohesion were determined.

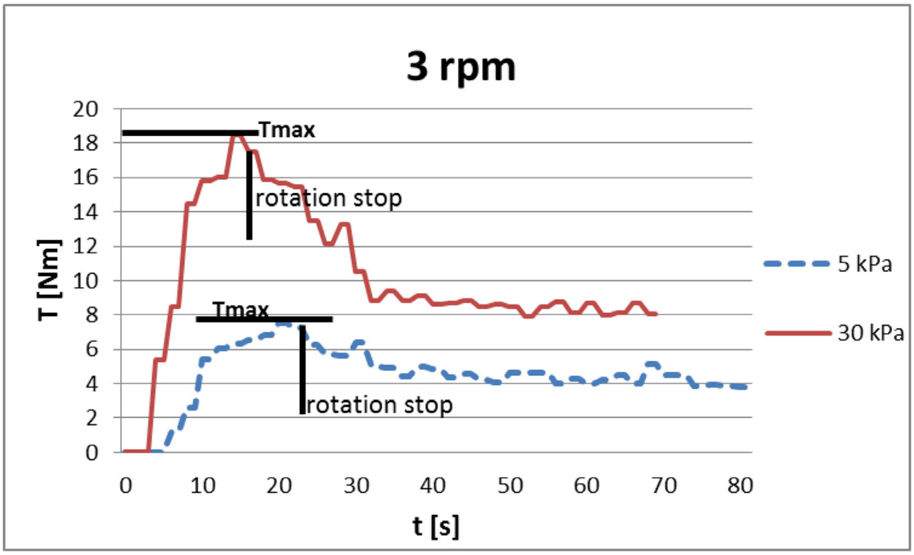


Fig. 2. Examples of torque-time curves obtained at normal pressure of 5 kPa and 30 kPa for rotational speed of 3 rpm.

Three repetitions of each measurement were performed. Each point of the presented plots is the mean value calculated and error bars denote the standard deviations.

3. Results

Fig. 2 shows the typical relationship between the torque and time for the sample under normal pressures of 5 kPa and 30 kPa sheared at a rotation speed of 3 rpm. The characteristic fluctuations of the values reflect the strong non-homogeneity of the material. The force necessary to shear the material along the cylindrical surface delineated by edges of the vane blades increases until the strength is exceeded, at which point the torque decreases for a short period. This is followed by a period of increase in the material resistance completed by the consecutive rupture of the sample. This sequence is repeated until the maximum strength is overcome at the maximum torque T_{max}. The shapes of the experimental curves obtained in these tests are similar to those observed in standard shear testing of granular materials. Detailed presentation of experimental curves obtained in direct shear tester for sawdust and woodchips was given in previous work of Stasiak et al. [18]. As shown in Fig. 2, the maximum measured torque values increase with an increase in the normal pressure applied to the material. Higher normal pressures produce steeper increases in $T(t)$ and reach the rupture point in a shorter time.

After the maximum torque value was reached, the movement of the rotor was stopped and the $T(t)$ curve decreased to its horizontal asymptote. During the first 15 s of relaxation, a sharp decrease in torque value was observed, followed by a flatter phase of decrease. The first phase of relaxation is sharper for higher normal pressures. The time at which the torque reaches the asymptotic value is comparable for different normal pressures. The decrease in torque during relaxation is larger for higher normal pressures. Under a normal pressure of 30 kPa, a 55% decrease in torque was observed, whereas a normal pressure of 5 kPa resulted in the torque decreasing by 50%. The asymptotic torque value is approximately 8 Nm for 30 kPa normal pressure and approximately 4 Nm for 5 kPa normal pressure.

Fig. 3 shows the maximum torque values obtained over the range 5–30 kPa for rotation speeds ranging from 3 to 13 rpm.

T_{max} increases as the normal pressure applied to the material increases. In the case of the minimum rotation speed, the maximum

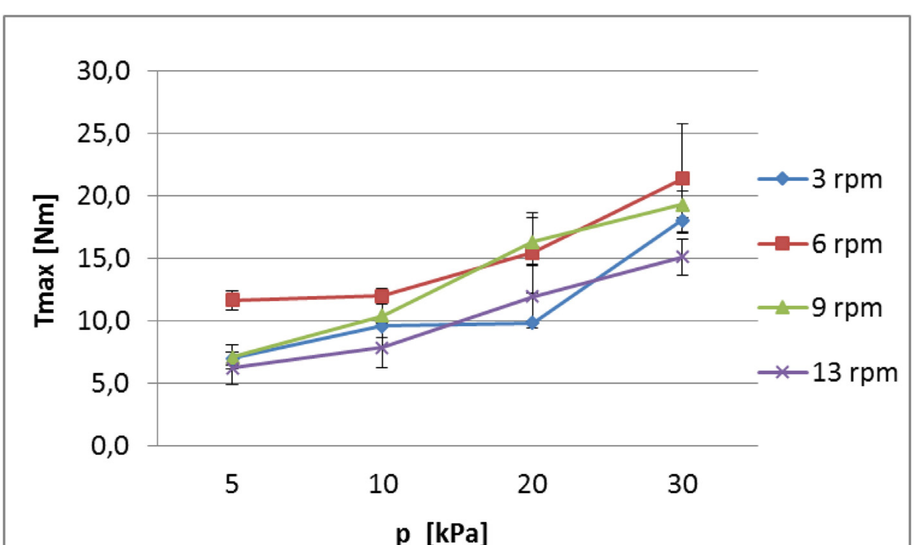


Fig. 3. Characteristics of maximum torque vs. normal pressure $T_{max}(p)$ for four values of rotation speed.

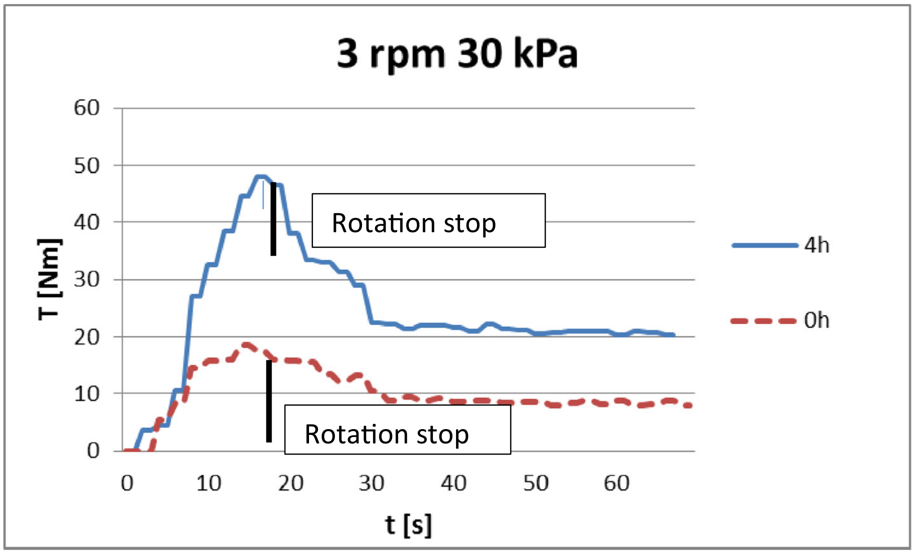


Fig. 4. Torque vs. time curves obtained at normal pressure of 30 kPa, for rotational speed of 3 rpm, after compressed for 0 h and 4 h.

torque increases from approximately 7 Nm to approximately 17 Nm. The T_{max} values increase by an average of 120% of the increase in normal pressure, and there are no significant differences between the maximum torque values at different rotation speeds. The strength increases in samples subjected to larger normal pressures, wherein the inter-particle bonds are also stronger. High standard deviations from the mean value of T_{max} were observed. This is a result of the irregular shapes and sizes of the woodchip particles. The standard deviations increase with an increase in the normal pressure.

During the storage of agro-granular materials and granular biomass for long periods of time, the strength of the stored material is observed to increase. This compression over time often results in stoppages of the flow in hoppers, and can even damage the silos. There is a need to determine the parameters of the granular biomass after being compressed for a long period of time. This simulates the natural circumstances that occur in real storage processes. Experiments with a compression time of 4 h give sufficient information on the increase in strength of the deposit. Fig. 4 presents the results of testing using forest woodchips compressed for 4 h. There was a significant increase in the maximum torque values with respect to the time for which the stress was acting on the probe of the material.

In the first phase of rotating the vane, the $T(t)$ curves are similar for material sheared immediately after pressure is applied and after compression for 4 h. The torque increases sharply and reaches a higher value in material subjected to compression for 4 h. The maximum value of T occurs after almost the same shearing time, independent of the compression time. The time from the relaxation of pressure in the material until the asymptotic value is reached is comparable for both tests. In both cases, the maximum of the curves occurs after approximately 15 s, and then the torque decreases to an asymptotic value of 50–55% approximately 30 s after the beginning of the test. The values of T_{max} obtained for compression times of 0 h and 4 h are presented in Fig. 5.

The maximum torque values determined for material subjected to compression are higher than those obtained for material sheared without previous compression. In the case of a rotation speed of 3 rpm and a normal pressure of 5 kPa, the maximum torque increases from approximately 8 Nm to approximately 15 Nm; for a normal pressure of 30 kPa, T_{max} increases from about 18 Nm to 47 Nm. For the highest rotation speed, at a normal pressure of 5 kPa, the maximum torque is comparable to those determined for lower rotation speeds. At a pressure of 30 kPa, an increase in rotation speed from 3 rpm to 13 rpm gives a slight decrease in T_{max}. As the quotient factor may be an efficient tool for estimating the flowability of material, as presented in US patent 4.181.023 [27], the quotient values of T_{max} for two pressure levels are presented in Table 2. The quotient is higher at higher normal pressure and increases with increasing rotation speed.

The effect of the water content of the material on the maximum torque value was analysed for moisture contents ranging from 10 to

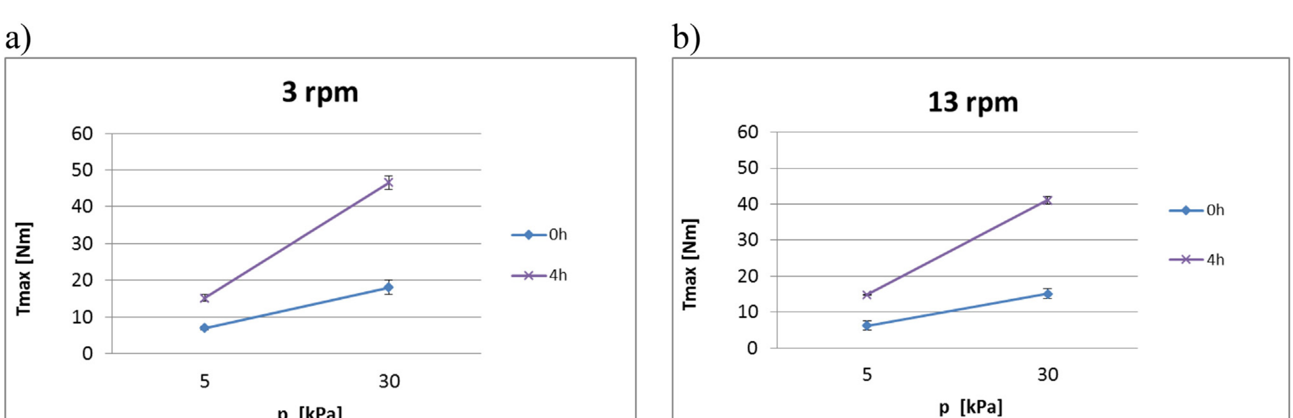


Fig. 5. Maximum values of torque T_{max} as dependent on normal pressure and compression times of 0 and 4 h for two rotational speeds 3 rpm (a) and 13 rpm (b).

Table 2
Torque quotient factor.

Normal pressure	Rotational speed	
	3 rpm	13 rpm
5 kPa	2.17	2.40
30 kPa	2.57	2.71

50% at two rotation speeds. Fig. 6 presents the relationship between the maximum torque value and normal pressure for rotation speeds of 3 rpm and 13 rpm and for moisture contents of 10, 30, and 50%.

An increase in moisture content results in an increase in T_{max} for both tested speeds. For the maximum normal pressure and a rotation speed of 3 rpm, T_{max} increases by approximately 130% as the moisture content increases from 10% to 50%, whereas for the minimum normal pressure and higher rotation speed, the torque increases by 200%.

Based on the measured maximum torque, the shear strength τ was calculated according to ASTM standard D2573 [33] regarding the vane test. The shear pressure was calculated on the assumption that its distribution is uniform across the bases and generatrix of a cylinder circumscribed by the edges of the moving rotor. This assumption allows τ to be calculated as follows:

$$\tau = T/K, \tag{1}$$

where T is the torque and K is a constant dependent on the vane dimensions given by

$$K = \pi D^2 H/2 \cdot (1 + D/3H) \cdot 10^{-6}. \tag{2}$$

In Eq. (2), D and H denote the diameter and height of the rotor.

There are some different methods of calculation of shear stress in these type of testers. One of the approaches is use in mechanically stirred aerated bed was particularly described in the paper of [34]. Table 3 presents the shear strength values calculated for compression times of 0 h and 4 h and moisture contents of 10% and 50%, subjected to normal pressures of 5 kPa and 30 kPa. Calculations were made for rotation speeds of 3 rpm and 13 rpm. The lowest shear strength value was obtained for uncompressed material with 10% moisture content at a pressure of 5 kPa. For a rotation speed of 3 rpm, the shear strength is $\tau = 3.15$ kPa, decreasing to 2.7 kPa at 13 rpm. The shear strength increases with an increase in moisture content and compression time.

Table 4 presents the shear strength values τ_{max} obtained in a Jenike shear tester for normal pressures of 15 kPa and 30 kPa. The values of τ_{max} obtained in the Jenike shear test are higher than those obtained in our VST under similar normal pressures. This is probably a result of different methods of imposing the load in the two testers. In the Jenike tester, the load is applied in the normal direction with respect to the shear path, whereas the load is parallel to the shear path in the vane tester. Thus, the real pressure at the shear surface in the VST is lower than rated.

According to the results obtained from the Jenike shear tester, the moisture content has no influence on the shear strength, which agrees with our earlier findings [18]. The value of τ_{max} under a normal pressure of 7.5 kPa is approximately 7.02 kPa, whereas for a normal pressure of 30 kPa, it is approximately 21 kPa.

The material parameters obtained by the Jenike shear tester are presented in Table 5.

The angle of internal friction was found to range from 29 to 33°, the effective angle of internal friction ranged from 32 to 40°, and the cohesion varied from 2.5–4.3 kPa. The tendency of all parameters to increase with an increase in moisture content was observed, although these effects are not statistically significant. Higher values of the angle of internal friction and effective angle of internal friction were obtained for lower values of the normal pressure for all moisture contents. Greater cohesion occurs under higher normal pressures during shearing. The flowability index classified the material as cohesive (>0.25) and easy flowing ($0.1 < i < 0.25$).

4. Discussion

In this study, a device for determining the shear torque in granular biomass was developed. The tests were performed for consolidated samples of forest woodchips, which is a material composed of non-uniform and irregularly shaped particles. A literature review showed that despite a large number of various standard procedures, there is no universal method for determining the mechanical properties of all granular materials. Although a number of devices and methods have been proposed for measuring the mechanical parameters of particulate solids, further solutions and an examination of the range of application of existing methods are required. Faced with an increasing interest in granular biomass and the scale of its application, there is a need to elaborate new devices and test procedures to determine its characteristics.

The objective of this study was to construct a prototype VST and develop a procedure to measure the torque with respect to displacement and determine the shear strength of consolidated samples of granular biomass. The proposed method is based on the vane shear method developed for rheological examinations of various materials [38]. The vane shear method has also been examined for highly concentrated biomass [30], modified lignocellulosic biomass suspension [31], and biomass of animal origin such as cow manure [35]. To date, the VST has not been used for the analysis of properties of raw forest

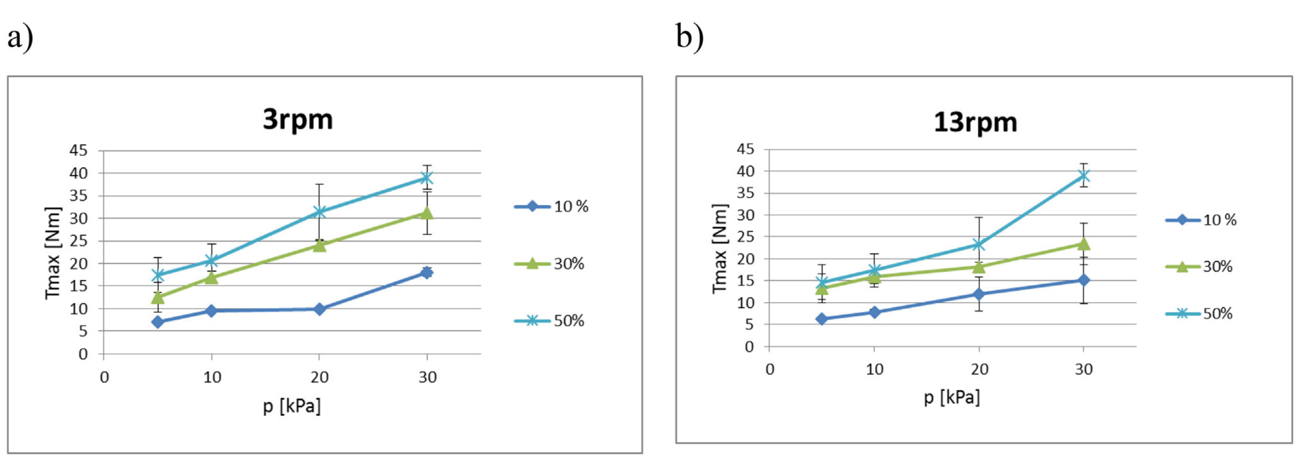


Fig. 6. The evolution of the maximum torque with normal pressure for material with different moisture contents, at rotational speeds of: (a) 3 rpm and (b) 13 rpm.

Table 3
Calculated shear strength τ obtained under different test conditions.

Test parameters	5 kPa 10% m.c.	5 kPa 4 h compression 10% m.c.	5 kPa 50% m.c.	30 kPa 10% m.c.	30 kPa 4 h compression 10% m.c.	30 kPa 50% m.c.
3 rpm	3.15 ± 0.32 kPa	6.76 ± 0.15 kPa	8.12 ± 0.09 kPa	8.12 ± 0.15 kPa	20.75 ± 3.00 kPa	17.14 ± 1.56 kPa
13 rpm	2.70 ± 0.25 kPa	7.21 ± 0.25 kPa	7.21 ± 0.11 kPa	6.76 ± 0.28 kPa	18.49 ± 2.50 kPa	17.14 ± 2.06 kPa

Table 4
Shear strength τ_{max} measured with Jenike shear tester.

Moisture content (%)	Consolidation normal pressure and normal pressure during shearing kPa			
	15 7.5	15 15	30 15	30 30
10	7.02 ± 0.35	11.57 ± 0.26	12.06 ± 0.80	20.74 ± 0.36
20	7.40 ± 0.13	11.77 ± 0.64	12.36 ± 0.10	19.45 ± 0.52
30	7.45 ± 0.53	12.60 ± 0.11	13.14 ± 0.35	21.85 ± 1.04
40	7.66 ± 0.73	12.56 ± 0.84	13.33 ± 0.62	21.68 ± 0.60
50	7.29 ± 0.63	12.23 ± 1.31	13.66 ± 1.24	22.72 ± 1.82

biomass such as forest woodchips. Therefore, in this study, the modified method was elaborated and its efficacy for the determination of granular biomass was verified.

The experimental results presented in this paper are comparable with data obtained for hammer milled corn stover at rotation speeds of 50 rpm [30,31]. However, these studies reported a strong influence of the rotation speed on the torque values, which is the opposite of our results. The torque values obtained in our experiments are higher than those obtained by Amiri et al. [35] for cow manure. The authors found that the maximum value of torque ranged from approximately 0.8–2.4 Nm and was affected by rotation speed and moisture content level. The torque in cow manure increased with an increase in rotation speed, but no significant dependence between the torque in woodchips and the rotation speed was observed in this study. This is probably a result of the higher water content of the manure, causing it to behave as a viscous material, i.e. with shear strength dependent on shear velocity. An increase in torque value with increasing moisture content in woodchips was noted, similar to the findings of Amiri et al. [35]. A decrease in shear pressure with an increase in rotation speed in forest biomass was observed by Przywara et al. [23], which conflicts with the results presented in this study. The reason for these discrepancies is probably the higher homogeneity of sawdust mixtures. The different mechanical characteristics of sawdust and woodchips have been reported by Stasiak et al. [18].

The relationships among the torque values and shear pressure with respect to the normal pressure broadly agree with the results presented in previous research on forest woodchips using the standard Jenike test [18]. In this previous paper, the shear vs. displacement characteristics were not influenced by moisture content, contrary to the results obtained during vane shear testing. This is probably because of differences in the shear path and geometry of the two testers. In a direct shear box, the ratio between the height of the material sample and its diameter is approximately 0.5, whereas in the VST, the ratio is approximately 1. The ratio of the maximum torques obtained with and without compression may be regarded as a measure of flowability. US patent 4.181.023 describes a device for determining the flowability of rubber powder. The authors recommended four distinct ranges of the quotient value (<2, 2–4, 4–6, and >6). In the case of rubber powder, a quotient value of <2 characterized good flowability, whereas a quotient of >6 corresponded to unsatisfactory flowability. In the case of our experiments, the quotient ranged from 2.17 to 2.71. It might be expected that, for woodchips and general granular biomass, the ranges of flowability indices would be different, as the particles are irregularly shaped and of various sizes, and have lower resilience than rubber powder. However, an adaptation of the method may be possible.

The results regarding shear strength are similar to those obtained by Stasiak et al. [18] using a direct shear tester for woodchips. The shear strength determined with the VST increased with an increase in moisture content, whereas the direct shear test values indicate strength parameters that are independent of moisture content. The values of shear strength obtained from the VST are slightly smaller than those obtained for the same normal pressure in the direct shear tester. The probable reason for this behaviour is the difference in the direction of loading relative to the direction of shearing. The sources of differences between results provided by two testers may be also the fact, that particles are relatively large compared to the thickness of the Jenike shear cell. On the other hand, the diameter of the Jenike cell, that is the distance between the leading and trailing edge of the sheared volume are large when compared to the average distance between vanes in the VST. Another difference might be induced by the filling procedure that, given the large relative size of the particles with respect to the Jenike cell thickness, may favor the alignment of particle along the shear plane. This is not the case in the vane tester where particles would be more free to keep a casual orientation while filling.

5. Conclusions

The proposed VST was found to be an efficient tool for determining the torque $T(t)$ of forest woodchips. An increase in normal pressure resulted in a steeper increase in $T(t)$ and a shorter time to reach the rupture point. The point at which the asymptotic torque was reached was similar for different pressures. The decrease in torque value during relaxation was higher for higher normal pressures.

Table 5
Material parameters obtained in Jenike shear tester.

	Moisture content (%)	Normal pressure (kPa)	Angle of internal friction (°)	Effective angle of internal friction (°)	Cohesion (kPa)	Flowability index
Woodchips	10	15	31.3 ± 0.5	37.9 ± 0.7	2.5 ± 0.5	0.2
		30	29.8 ± 1.5	34.7 ± 0.5	3.5 ± 1.3	0.2
	20	15	30.2 ± 3.0	38.6 ± 1.4	3.0 ± 0.4	0.3
		30	29.3 ± 1.3	32.8 ± 1.4	4.9 ± 0.5	0.3
	30	15	32.5 ± 1.3	40.1 ± 0.4	2.9 ± 0.6	0.3
		30	32.9 ± 2.6	37.4 ± 1.2	3.4 ± 1.0	0.2
	40	15	33.1 ± 2.7	40.3 ± 2.1	2.8 ± 0.9	0.3
		30	30.7 ± 1.4	36.0 ± 0.8	3.9 ± 0.9	0.2
	50	15	33.3 ± 3.7	39.4 ± 2.9	2.3 ± 0.3	0.2
		30	31.9 ± 0.6	37.7 ± 1.5	4.3 ± 1.4	0.2

The Vane Shear Tester is not a proper tool for determination of physical material parameters such as angle of internal friction and cohesion. However, it provides information about strength of tested material. Vane shear tester could be used to estimate the loads acting on screw conveyor while emptying of the silos or to compare quickly the different lots of material.

T_{max} increased with an increase in normal pressure and did not change across the range of applied rotation speeds considered here. The maximum torque values determined for compressed material were higher than those obtained for immediately sheared material. An increase in moisture content resulted in an increase in the value of T_{max}.

The results obtained with the new tester are in general agreement with those obtained from testing using the standard Jenike method [9], but testing with the new method is easier and less time consuming. Quantitative differences between the results obtained by the two methods are most probably a result of the different mode of load application and the geometry of the shear surface.

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