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SHEAR AND CRUSHING STRENGTHS OF WOOD PELLETS

This paper presents a methodology for determining the shear and crushing strengths of four types of wood pellets. Wood pellets are renewable and sustainable products that are obtained from wood biomass and used in combustion. Their mechanical characteristics are not well defined. To characterize wood pellets, their shear and crushing strengths should be measured along with their size, moisture content, density, abrasion, and chemical contents. The shear and crushing strengths were analysed for their dependence on density, considering if these strengths remain as independent properties or only an additional option for the producers. All results showed that the shear and crushing strengths were individual properties of wood pellets and that density greatly influenced these properties. Based on theoretical research, the admittance values of breaking and shear strengths were also estimated. These results can be used in wood combustion for creating fuels from waste wood.

Keywords: wood pellet; shear strength; crushing strength

Introduction

Woody biomass is a renewable energy source. Along with solar, geothermal, wind, or water energy sources, biomass can reduce emission and greenhouse gases compared with traditional fossil fuels. It is used in developing and developed countries [Bhattacharya and Abdul 2002; Boutin et al. 2007; Jehlickova and Morris 2007]. Moreover, biomass may be the only energy source of the future that can reduce global warming by means of its characteristics and conversion into fuels and chemicals [Kim and Dale 2003; Dhillon and von Wuelhlisch 2013]. Woody biomass is a sustainable product when its consumption does not exceed the annual increase of logged trees [Lundborg 1998; Gavrilescu 2008; Lakó et al. 2008; Lunguleasa et al. 2010]. It is very important to consider woody biomass sustainability and renew ability resulting from forest logging activities (cracked tops, bushes, etc.) or processing of raw wood into semi-finished products (lumber, oriented strand board, chipboard,

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medium density fiberboard, pulp, paper, etc.) or finished goods (furniture, doors, flooring, etc.).

The burning of woody biomass is a thermal process that emits pollutants, including carbon dioxide [Wilkins and Murray 1980]. Compared with anthracite coal, which was formed over millions of years, woody biomass regenerates in only a few decades. Furthermore, the emission of carbon dioxide is much lower, namely 83 g/MJ compared with 97 g/MJ for anthracite; the lowest value belongs to natural gas at 50 g/MJ [Demirbas 2001]. Woody biomass (along with other renewable sources) is considered the energy of the future in Europe [Wolf--Crowther et al. 2011] with a target contribution of 20% in 2020 for RES. World wood pellet consumption in 2012 was about 22 million tones, with Europe consuming 69% of the total mass,as seen in figure 1 [Gauthier 2014].

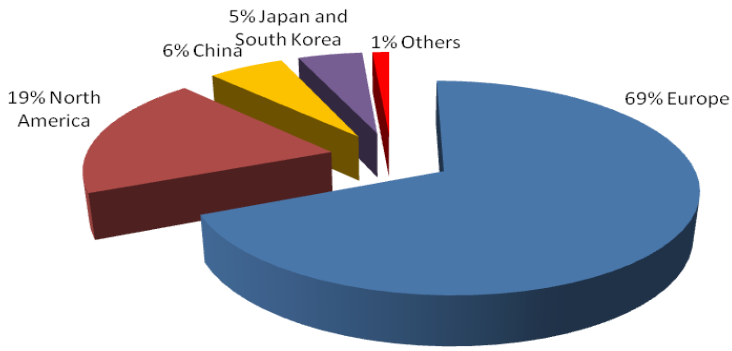

Fig. 1. Global wood pellet consumption in 2012 [adaptation from Gauthier 2014]

Woody biomass fuels are often in the form of pellets [Stelte et al. 2011]. Woody biomass pellets are superior products obtained by compressing chopped wood without extra additives. These products are compacted over 1000 kg/m^3, dried and maintained at10% moisture content, and packed in polyethylene film; thus, their calorific value is kept at a high level. By adding some natural additives, such as starch, sugar, soda, lye, lime, gypsum, or molasses, or by improving the surface consistency of the pellets with thermal treatments or lignin activation, the quality of these products is improved [Lunguleasa et al. 2015]. Another way to intensify the fuel calorific value is to mix in coal or another carbon component [Garcia et al. 2004; Junginger et al. 2008], but these additions result in harmful emissions.

Wood pellets must conform to standardized properties, which are often combined for pellets and briquettes, as ÖNORM M 7135 [2000] in Austria, DIN 51731 [1996] in Germany, SS 18 71 20 [1998] in Sweden, CTI-R 04/5 [2004] in Italy, CEN/TC 335 [2004], EN ISO 17225-1 [2014] and EN ISO 17225-2 [2014] for European wide. The main properties of pellets are: dimension (diameter and length), moisture content, bulk and effective density, mechanical durability or abrasion, heating value, chemical contents (sulphur, nitrogen, chlorine), impurities/foreign matter, etc. [Demirbas and Demirbas 2004; Verma et al. 2009]. Of these, density is one of the most important physical properties because it may influence all of the others. In this respect, the most restrictive density standard is ÖNORM M 7135 [2000], with a minimal accepted value of 1.12 g/cm^3. The DIN 51731 [1996] standard is less restrictive (1 to 1.2 g/cm^3). As the pellets are stored in factories, at customer sites, and during transportation, they are piled on top of each other, and some compression forces crush and destroy them. Therefore, the above-mentioned standards should also include the shear and crushing strengths. Shear and crushing strengths of wood pellets can become part of the mechanical properties along with mechanical durability.

The crushing and shear strengths of wooden pellets have been studied to some extent in other materials including glass, ceramics, concrete, mud, pyrite ash, bituminous coal, and polymeric waste [Zarringhalam et al. 2011; Sola and Atis 2012; Kersa et al. 2010; Mitchual et al. 2013]. Sometimes the resistance is described as the crushing force of briquettes (which is not adjusted for briquette size), or it is linearly correlated with the length of the briquettes. Usually the values are between 30 and 80 N/mm [Plištil et al. 2005]. There is a small linear correlation between briquette density and compressive strength [Lunguleasa 2010]. There are many practical studies about the use of wood or agricultural briquettes and pellets, but there are more studies about the influencing factors [Kaliyan and Morey 2009] including moisture content, tree species, or size and shape of briquettes and pellets [Rahman et al. 1989].

There are several ways to assess wood pellet strength, such as breaking strength (impact), falling strength, abrasion resistance, or technological durability [Kaliyan and Morey 2009]. A modern pellet production line uses a special order to obtain fodder pellets for livestock nutrition [States 1993]. The main mechanical feature of pellets of any kind (including those used as fertilizers in agriculture) is abrasion resistance or the technological durability [Teren and Hutar 1993], with the crushing and shear strengths not being mentioned. In another scenario, a plant with a circular carousel system can be used to determine pellet shear strength determination [NorvidanEng 1987]. During its rotation, the circular carousel places one pellet into an external hole, which passes before a cutter that chops the pellet. The pressure exerted by the cutter (the cutting force) is measured by a transducer. This process is disadvantageous because the pellet cutting force is considered equal to the shear force; in actuality, the cutting force is lower because the procedure uses cutting and not shearing. Moreover, the surface being sheared is not considered in determining the real shear strength.

Shear and crush strength values of the pellets have practical importance for users of pellets. If the pellets do not have good strengths, they will break easily during transportation and handling. In this way, inside of the furnaces reaches a large amount of dust and broken pellets, which will significantly reduce their combustion efficiency.

This study aims to create two simple and reliable methods for determining the shear and crushing strengths of wood pellets. Based on theoretical and experimental research, the interdependence of strengths and density aim to be examined in order to determine whether they should be included in the main properties of wood pellets. Finally, the admittance values of strengths aim to be also obtained.

Materials and methods

Four different types (as producer and species) of wood pellets (10 kg for each type) were purchased from the Dedeman hypermarket (Brasov, Romania). According to packaging labels, type 1 of pellets was made of spruce (*Picea abies*), type 2 from resinous species, type 3 from beech (*Fagus sylvatica*) and type 4 from oak (*Quercus robur*). All types of pellets had a diameter of 6 mm and did not contain other additives. Pellets from these sacks were used for each assessment, starting with dimensions and density and ending with the shear and crushing strengths. Both strengths were determined using a universal testing machine (ZwickRoell, Ulm, Germany), with specific devices and a low speed of acting force of about 10 mm/min.

a b

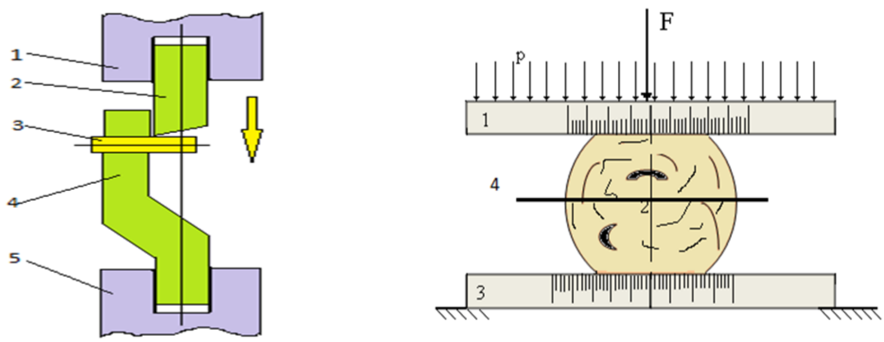

Fig. 2. Shear and crushing strength of pellets [Spirchez and Lunguleasa 2016]: a – shear strength (1 – superior pliers, 2 – shearing arm, 3 – pellet, 4 – inferior arm, 5 – inferior pliers); b – crushing strength (1 – superior platen, 2 – briquette, 3 – inferior platen, 4 – crushing section, p – specific pressure, F – force of crushing--disintegration)

Figures 2a and 2b present the determination of shear strength and crushing strength, respectively. As the shear and breaking strengths depend on the pellet density, the pellet dimensions (length and diameter) were first determined. The actual density of the pellets was set. The density of 100 individual pellets of each type was calculated. Because the wood pellets were too small to be marked, the position of each wood pellet was noted on a sheet of flat chipboard, and the dimensions were measured accurately with an electronic caliper to a precision of two decimals. The mass of each piece was determined with two-decimal precision, using an electronic balance. Based on these values, the volume, mass, and density (as the correlation between mass and volume of pellets at 10% moisture content) of each piece were evaluated. Given the regular cylindrical shape of the pellets, their actual density ρ_{ef} (g/cm^3), as ratio between mass and volume ($\pi d^2 l/4$), was calculated (equation 1):

$$\rho_{ef} = \frac{4m}{\pi \cdot d^2 \cdot l} \tag{1}$$

where: m is the pellet mass (g), d is the pellet diameter (cm) and l is the pellet length (cm).

For bulk density calculations, a scaled cylinder with a 50 mm diameter was filled with pellets, which were placed in the horizontal orientation. The volume (cm^3) of pellets within the cylinder was noted. The cylinder was weighed before and after the pellets were added, and the difference between the initial and final mass was the pellet mass. Twenty replicates were performed to determine bulk density, as a ratio between mass of pellets and volume of cylinder (equation 2):

$$\rho_{bulk} = \frac{4(m_t - m_i)}{\pi \cdot d^2 \cdot h} \tag{2}$$

where: ρ_{bulk} is bulk density (g/cm^3), m_t is the total mass of the cylinder with pellets (g), m_i is the initial mass of the empty cylinder (g), d is the inner cylinder diameter (cm), and h is the height of pellets in the cylinder (cm).

The shear strength (for 5 pellets at the same time, as the force values were low) and the crushing strength (for a single pellet) were determined via the ratio between the force F and the section area, namely $d \cdot l$ for crushing strength and cross area of 5 pellets $5 \cdot \pi d^2/4$ (equations 3 and 4):

$$\sigma_b = \frac{F}{d \cdot l} \tag{3}$$

$$\tau_s = \frac{4 \cdot F}{5 \cdot \pi \cdot d^2} \tag{4}$$

where: σ_b is the crushing strength (N/mm^2), τ_s is the shear strength (N/mm^2), F is the crushing or shear force (N), d is the pellet diameter (mm), l is the pellet length (mm).

The crushing and shear strengths were determined for 4 groups of 50 pellets each, and the averages and standard deviations were calculated. In decreasing order of density and strength, the groups were designated as batch 1, batch 2, batch 3, and batch 4.

Results and discussion

The dimensional features of the four types of pellets are presented in table 1. The diameter of the pellets was within European standard specifications as ÖNORM M7135 [2000], i.e., 4 to10 mm; the average length of the pellets was within the general requirements of being shorter than 50 mm, or shorter than 5 times their average diameter. These values were consistent with previous reports [Teren and Hutar 1993; Stelte et al. 2011]. The average values for density, crushing strength, and shear strength for the four types of wood pellets are shown in table 2.

Table 1. Dimensional features of pellets

Features		Type 1	Type 2	Type 3
Diameter (mm)	Range	6.06-6.82	6.01-6.27	5.92-6.39
	Average	6.17	6.07	6.02
	Standard Deviation	0.14	0.05	0.08
Length (mm)	Range	11.09-26.39	8.72-30.33	11.38-28.00
	Average	16.25	18.37	19.68
	Standard Deviation	3.17	3.46	4.12

Table 2. Density and strength properties

Batch	Density (g/cm^3)	Bulk density (g/cm^3)	Crushing strength (N/mm^2)	Shear strength (N/mm^2)
1	1.119	0.667	5.489	2.733
2	1.115	0.602	5.408	1.902
3	1.112	0.619	4.824	1.629
4	1.008	0.673	3.447	1.471

For the ÖNORM M 7135 [2000] standard (density greater than 1.12 g/cm^3), all values were under the specification by 0.08 to16%. While these lower values could affect the strength under, other European standards as EN ISO 17225-2 [2014] are less restrictive (from 1.0 to 1.2 g/cm^3). All four batches of pellets complied with the less restrictive standards.

Next, it was determined whether strength and density were interdependent by analysis of figure 3, i.e., the angle of the three straight lines. In each group of pellets, the influence of density on the crushing and shear strengths was analysed as a linear trend. Given the $y = m \cdot x + n$ linear equation of pellet density, with $m = tg\alpha$, a very narrow angle was observed in the straight line of density with the Ox horizontal of 1.89 degrees only, and another larger of 23 degrees for the shear strength, and of 38 degrees for crushing strength. Therefore, there was a direct correlation between the pellet density and the two strengths under analysis. This result was another reason for determining these strengths, especially due to the high intensity of such influence.

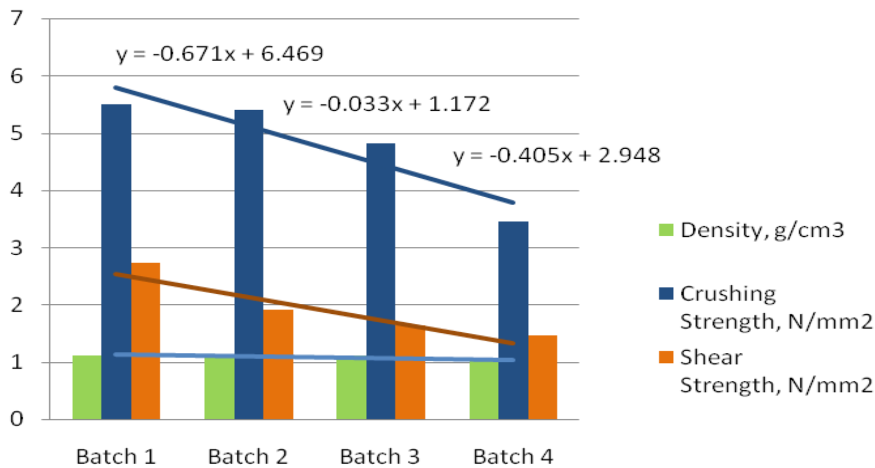

Fig. 3. Variations in density, shear and breaking strengths of pellets

The admittance value of crushing and shear strengths

Strength determination requires a reference value for comparison, usually a superior or inferior limiting value, as EN ISO 17225-1 [2014] stipulates that. In this study, the minimum value was used as a reference from which all average measured values must start. The theoretical model of wood pellet arrangement used to determine this value is presented in figure 4.

A wood pellet at the bottom of a stack undergoes a vertical compression by crushing or shearing (obtaining the original fig. 4) through the adjoining pellets that arearranged as a downward facing triangle section. For shear strength, the total force acting on the base pellet is only half of the breaking force.

The acting force of the model was expressed as $F = M \cdot g$, where M is the mass of all wood pellets (kg) in a triangular shape and g is the gravitational acceleration (9.81 N/kg). In the case of shear/crushing strength, the total mass was given by the product of the average mass of one pellet (m) and total number of pellets (N), therefore $F = m \cdot N \cdot g$. For a vertical plan model of crushing strength (Fig. 4a), each row of pellets increases the total number of pellets pressing on the bottom pellet, such that the total number of pellets in a stack (N) is equal to $n\,(n + 1)/2$, where n is the number of rows. As summarized in equation (5), the force F force acting on the base pellet (N) is:

$$F = m \cdot g \frac{n(n+1)}{2} \qquad (5)$$

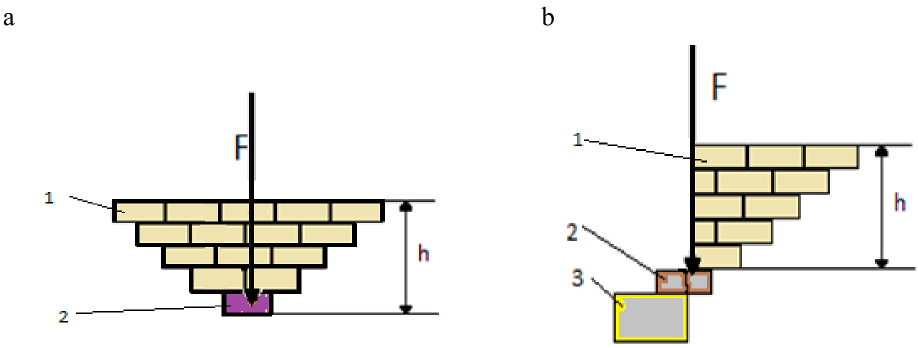

Fig. 4. Pellet arrangement subject to breaking (a) and shear strength (b): *F* – force, *h* – height of the pellet stack, 1 – current pellet, 2 – pellet subjected to force *F*; 3 – counterknife support

If a three-dimensional model is used, the number of pellets that act on the base pellets is higher and corresponds to a quadrilateral pyramid pointing downwards, each row being increased by its square, such that $N = n(n+1)(2n+1)/6$. Thus, the F force acting on the base pellet (N) becomes:

$$F = m \cdot g \frac{n(n+1)(2n+1)}{6} \tag{6}$$

For shear strength, the force is half of the value calculated from equation (6), i.e.:

$$F = m \cdot g \frac{n(n+1)(2n+1)}{12} \tag{7}$$

Equations (6) and (7) represent the general crushing and shear forces, which may be customized for a sack of pellets, where the height was about 150 mm, i.e., 25 rows of pellets, each with the average diameter of 6 mm. Thus, the crushing and shear forces for a pellet with the average mass of 0.6 g were 32.52 N and 16.26 N, respectively, meaning that the crushing force and shear force were about 32% and 16%, respectively, of the total weight of the sack. To convert the values into strengths, the pellet areas subject to crushing and shear were determined (equations 3 and 4). These values of strengths were determined as 4.6×10^{-4} N/mm^2 for breaking strength and 0.02 N/mm^2 for shear strength. Because sacks of pellets are transported on pallets with 6 to 8 rows of sacks per pallet, the values of the strengths should be significantly higher, i.e. 2.7 to 3.6×10^{-3} N/mm^2 for crushing strength and 0.12-0.16 N/mm^2 for shear strength. A shock coefficient of 4 during manipulation must be considered, as the sacks may fall or overlap. In such conditions, the admittance values of the two strengths become 0.014 N/mm^2 for crushing and 0.6 N/mm^2 for shear. It must be noted that pellets shear occurs 42 times more often than they crush during manipulation. This statistic corresponds to the complaints of pellet producers, as the dimensions (especially the length) when leaving the factory differ from those of the products arriving at their final destination.

The allowable values of shear and breaking strengths are minimal in our analysis. Regarding the admittance value of strengths, all four kinds of wood pellets were evaluated by comparing the actual values of the strengths with the minimum reference ones obtained before. All four batches of pellets complied from this point of view; all were above the allowable value. For instance, in the case of batch 1, real values of 5.4 and 2.7 N/mm^2 for crushing and shear strength, respectively, are certainly more than the allowable values of 0.014 N/mm^2 for crushing and 0.6 N/mm^2 for shear strength.

Conclusions

The two methods to determine the shear and crushing strength for wood pellets are very simple and easy and only require a universal testing machine and specific devices. After determining the density, shear strength, and breaking strength of wood pellets, the influence of density on strength was observed and analysed. Thus, as a conclusion, it is recommended that shear and crushing strengths should be used to quantify the quality of pellets. For other lignocelluloses raw material (straw, forage plants, algae, etc) used in pellet manufacturing, more research is necessary to see if the above tendency is the same.

The allowable shear and crushing strength values of 0.014 N/mm^2 and 0.6 N/mm^2, respectively, may cover the complete real shear and crushing strengths, even for the most restrictive standards. Determination of shear and breaking strengths will elucidate the compactness and consistency of wood pellets, thus improving the quality of these products. This study has practical importance for producers and users of wood pellets. The demonstrated model can be also used in timber storage and drying, log storage and other storing materials.

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