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The Impact of Particles Comminution on Mechanical Durability of Wheat Straw Briquettes

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Abstract: Briquetting is one of the recommended biomass agglomeration processes. The material subjected to briquetting gains valuable functional features related to higher energy density, appropriate moisture content, and increased bulk density. However, the briquettes need high mechanical durability to maintain high quality during transportation, loading, and other logistic steps before they will be delivered to the final consumer and utilized for energy purposes. The mechanical durability depends on many factors, including the particles comminution of the compacted biomass. Therefore, the aim of this study was to analyze the impact of particle comminution on the mechanical durability of wheat straw briquettes. The research was carried out in accordance with the international standard for solid biofuels PN-EN ISO 17831-1:2016-02. The briquettes were produced from three different fractions: 0–2 mm, 2–15 mm, and 15–45 mm. To obtain more data related to the mechanical durability of briquettes, the tests were also carried out outside the ISO standard conditions. During the investigations, the working chamber operation time was extended from 5 to 60 min, and the rotational speed of the working chamber was increased to 25 and 30 rpm, respectively. The results indicated that the mechanical durability index (Du) of briquettes decreases along with the increase in the particle size. According to the PN-EN ISO 17831-1:2016-02 standard, the highest mechanical durability was achieved for the 0–2 mm fraction (Du = 91.17%) followed by the 2–15 mm fraction (Du = 88.12%), and the lowest was achieved for the 15–45 mm fraction (Du = 84.48%). It was noticed that the increase in the working chamber operation time resulted in a decrease of the Du value. Moreover, the difference in mechanical durability (between t_5 = 5 min and t_{60} = 60 min) was greater for a larger fraction (ΔDu = 16.26% for 0–2 mm fraction, ΔDu = 21.04% for 2–15 mm fraction, and ΔDu = 23.43% for 15–45 mm fraction). It was also observed that the increase of the rotational speed of the working chamber caused a slight decrease in the value of the mechanical durability of briquettes for all investigated fractions.

Keywords: mechanical durability; particles comminution; wheat straw briquettes

1. Introduction

The forecast for the coming future indicates that by 2040, the global electricity demand will grow by 2.1% annually [1]. The increasing electricity demand resulting from the economic development of many countries globally and the significant growth of the population forces the use of more raw materials to meet these needs [2]. In terms of energy, the European Union (EU) strategy recommends increasing the share of renewables, especially biomass, which is the third-largest energy source in the world [3]. It is predicted that the total technical potential for biomass use in 2050 will be in the range of 55–325 EJ·year^{-1} [4]. Unfortunately, the use of biomass very often requires its adaptation to combustion processes through various pre-treatment processes [5]. The main reason of this is a low density of biomass and high moisture content, which makes transport, storage, and thermal conversion difficult. The most desirable form of biomass for energy purposes are pellets and briquettes [6], which results from their increased energy density, lower moisture content, and multiplied bulk density [7] enabling transport over longer distances and safe storage. Additionally, burning biomass in the form of briquettes is more effective and reduces greenhouse gas emissions, NO_x, and SO_2 [8].

However, the biomass briquettes have to meet many requirements in relation to their physical and chemical properties to be of high quality. Several parameters are used for their valorization [9–14], including mechanical durability [15]. The mechanical durability relates to the shock and/or abrasion resistance of compressed (agglomerated) material due to its handling and transport [16]. Therefore, it is one of the most important parameters of compacted forms of biomass in assessing their quality and suitability [17–20]. The high value of the mechanical durability index confirms the appropriate parameters of the compaction process in briquette production [19–21]. However, the mechanical durability of briquettes/pellets depends on several factors, such as the operating temperature and pressure of the agglomeration process, type of the compacting machine, storage conditions, and applied additives as well as properties of the raw material [17,22–24].

Among other factors, the particle size of the material to be agglomerated is a crucial parameter influencing the mechanical durability [25]. Different works indicate that the fractions up to 2 mm are characterized by a higher density and durability of the material due to the larger bonding area [26,27]. In turn, Grover and Marisha [28] showed that a 6–8 mm fraction should be used for this briquetting purpose, whereas Brunerová and Brožek [29] concluded that the optimal fraction of the material depends on the substrate used and its individual properties. In addition, other studies report that a greater mechanical durability occurs with increasing particles used for briquettes production [30,31]. Moreover, the biomass fraction before the briquetting process is important because it affects the costs of material grinding. Since briquettes intended for energy purposes are subject to various types of damage during transport, handling, and storage as a result of the impact, friction, or uncontrolled crushing, they must be characterized by high mechanical durability. This issue is of particular importance due to the growing interest in replacing hard coal with biomass as an alternative solid renewable fuel. As a result, the distance of biomass transport to the final consumer should be expected to increase, which increases the risk of its damage and quality reduction. In fact, in the case of individual users, the briquettes are very often placed and delivered on pallets in plastic bags, which reduces the damages [32]. However, in the case of middle-sized energy communities, the briquettes are transported in their loose form, which requires their high durability. If the production process is not properly planned, the briquettes might be too soft to be transported [33].

As a result, the behavior of briquettes made of various biomass fractions exposed to long-term effects of factors occurring in transport is important from the point of view of the production process and quality maintenance after delivery to the end user. Currently, it is also popular to use additional briquettes pre-treatment and processing (e.g., torrefaction) in order to improve their energy properties. Due to such processes and the additional transport, loading, and storage steps of the logistic chain, briquettes are more prone to mechanical damage. In the literature, there are little data on the tests of mechanical durability of briquettes in conditions that exceed the ISO standard and performed with the use of the same equipment. It seems justified to carry out research simulating the behavior of briquettes during multi-stage logistics processes.

This research aimed to analyze the influence of the particles comminution on the mechanical durability index of briquettes made of wheat straw using the apparatus in accordance with PN-EN ISO 17831-2: 2016-02 standard. The tests were performed (i) in the conditions in line with ISO standard,

(ii) in the range of operation time of the apparatus from 5 to 60 min, (iii) in the range of the rotational speed of the working chamber from 21 to 30 rpm.

Wheat straw was selected for investigations, as it is one of the most popular substrates for briquettes production and used for energy purposes. The EU annual potential of crop residues of straw amounts to 258 mln Mg d.m. (including 110 mln Mg d.m. from wheat) [34,35]. In Poland, the yearly resources of straw are also significant (ca. 25 mln of tonnes), and the share of wheat is ca. 30% [36].

2. Materials and Methods

2.1. Materials Used in the Experiment and Its Pre-Treatment

Wheat straw was selected as the research material. The material was stored in the form of round bale under a roof. The straw was shredded in a knife mill RU-3M (FNRJ, Jawor, Poland). Then, the comminuted straw was sieved manually using three laboratory sieves. The mesh size of the screen was 2 mm, 15 mm, and 45 mm, respectively. The sieves were used in order from largest to smallest size. As a result, three samples fractions (minimum 50 kg each) of the wheat straw (0–2 mm, 2–15 mm, 15–45 mm) were prepared.

2.2. Moisture Measurement and Briquette Preparation Procedure

Before the pressure agglomeration process (after the milling process), the moisture content (MC) in the wheat straw was determined. The analysis was performed according to PN-EN ISO 18134-2:2017-03E standard [37] using a drying oven (drying temperature: 105 °C, drying time: 24 h). The tests were repeated three times. The following formula was used:

$$MC = \frac{m_b - m_c}{m_b - m_a} \cdot 100\% \quad (1)$$

where MC—the moisture content of the sample (%); m_a—the mass of the empty crucible (g); m_b—mass of the crucible with the sample in the analytical state (g); m_c—mass of the crucible with the sample after drying (g).

The prepared fractions were subjected to pressure agglomeration with the use of a hydraulic briquetting machine STANDARD (Por Ecomec, Brescia, Italy) (Figure 1). The technical data of the machine are presented in Table 1.

Figure 1. Hydraulic briquetting machine STANDARD.

For each of the three fractions, 30 kg of briquette was produced. To ensure the same storage conditions for the research material and limit the influence of external factors, the briquettes were kept in plastic bags.

Table 1. Technical data of the hydraulic briquetting machine used.

Parameter	Unit	Result
Producer	-	Por Ecomec
Model	-	STANDARD
Product diameter	mm	65
Maximum briquette length	mm	50
Engine power	kW	5.55
Hydraulic crushing	$kg{\cdot}cm^{-2}$	1000

2.3. Mechanical Durability Test

The mechanical durability test of briquettes was carried out in accordance with PN-EN ISO 17831-2: 2016-02 standard [16] For this purpose, a device for testing the mechanical durability of briquettes was used (Łukomet, Całowanie, Poland) (Figure 2). The investigation procedure was as follows: 2000 g (±100 g) of the briquettes were put into the working chamber. The rotational speed of the chamber was n_1 = 21 rpm, whereas the operation time of the working chamber (t) was t_5 = 5 min.

Figure 2. Apparatus for testing the mechanical durability of briquettes: (**a**) side view, (**b**) rear view, (**c**) working chamber dimensions.

After the test, the entire content of the chamber with the investigated briquettes was sieved through a sieve with a mesh diameter of 45 mm applying circular movements. Then, the mass of the briquettes left on the sieve was determined using the electronic scale PS 6100.R1.M (Radwag, Psary, Poland) with an accuracy of 0.1 g. Finally, the mechanical durability index (Du) of briquettes was calculated using the following formula:

$$\mathrm{Du} = \frac{m_2}{m_1} \cdot 100\% \quad (2)$$

where Du—mechanical durability index of briquettes (%), m_2—mass of briquettes left on the 45 mm sieve after the test and sieving (g), and m_1—mass of briquettes inserted into the working chamber (g).

In addition to performing the tests in accordance with ISO standard, the research was carried out in a wider range of operating conditions. Namely, the test of mechanical durability of briquettes was extended until 60 min (the operation time of the working chamber t) with the determination of the mechanical durability index Du every 5 min (t_5 = 5 min, t_{10} = 10 min, etc.). In these tests, after each attempt, the entire material (over-screen and under-screen fraction) was put again into the working chamber. Moreover, the same procedure was applied for an increased number of rotations of the working chamber (n_2 = 25 rpm and n_3 = 30 rpm). Each test was performed three times.

2.4. Statistical Analysis

Within the research analysis, the standard deviation and coefficient of variation for all tests were determined. Morover, the statistical analysis (at p-value < 0.05) applying a two-way analysis of variance (ANOVA) was performed. The test was focused on the elaboration of statistical significance of the influence of the rotational speed of the working chamber and the working chamber operation time on mechanical durability of briquettes for the fractions under analysis. Additionally, for the considered fractions, the interaction between these parameters was investigated as well.

3. Results and Discussion

3.1. The Moisture Content in the Briquettes

One of the factors influencing the mechanical durability of briquettes is the moisture content in the material [38]. The MC in the analyzed wheat straw briquettes was 12.02%. The standard deviation (SD) for the moisture content was 0.05%. Hebda and Złobecki [39] investigated the relationship between the mechanical durability of straw briquettes and its moisture content. The authors recommended the optimal moisture content in the material intended for briquettes ca. 15%. Similar studies were performed by Brožek [40], suggesting the moisture content of 12% in the material as the most appropriate value. The moisture content in briquettes should not be too high due to the decrease in the energy value of the briquette, thus deteriorating their combustion quality [41].

3.2. The Mechanical Durability Index—PN-EN ISO 17831-2: 2016-02 Standard

In the test performed in accordance with PN-EN ISO 17831-2: 2016-02 standard, the briquettes with the lowest degree of fragmentation (the fraction of 0–2 mm) were characterized by the highest mechanical durability (Table 2). The average value of the mechanical durability index for this fraction amounted to 91.17% ± 1.18%. The increase of the wheat straw particles resulted in a decrease of the mechanical durability index of briquettes; for the 2–15 mm fraction, the average value Du = 88.12% ± 0.40% was determined. Whereas, in the case of the 15–45 mm fraction, a further reduction of mechanical durability was detected. The average value of the Du index was 84.48% ± 1.08%. The tested fractions' coefficient of variation should be considered relatively close to each other (range 0.46–1.30%), which indicates a small dispersion of the obtained values of mechanical durability in the tests.

Table 2. Mechanical durability of wheat straw briquettes (n_1 = 21 rpm, t_5 = 5 min).

Fraction Range	Average Value of Mechanical Durability (D_u)	Standard Deviation (SD)	Coefficient of Variation
mm	%	%	%
0–2	91.17	1.18	1.30
2–15	88.12	0.40	0.46
15–45	84.48	1.08	1.28

Although a significant decrease of the mechanical durability index for a larger fraction was observed, the Du values can be considered satisfactory. The research of other authors showed that briquettes made of plant materials should be characterized by the higher mechanical durability index Du, exceeding 80% [42–44]. However, these values are not always achieved. Borkowski and Gendek [45], examining briquettes made of a mixture of sawdust of various species of forest trees, observed the complete disintegration of the briquette (Du = 0%), However, this result was caused by the biomass having too much humidity, which was not reduced to an appropriate level. In this experiment, it was also observed that the mechanical durability depends on the degree of fragmentation of the particles from which the briquette was made. Several works in the literature focused on this research problem. Table 3 presents the main works investigating the influence of fraction grinding on the mechanical durability of briquettes.

Table 3. Research investigating the effect of fraction grinding on the mechanical durability of briquettes.

Source	Briquetted Material	Tested Fraction	Test Standard	The Range of Mechanical Durability
Muntean et al. [46]	Hemp, Miscanthus, Apple Wood	4 mm, 8 mm, 12 mm	EN ISO 17831-2:2015 with respect to EN ISO 16559:2014	91.00–98.00%
Niedziółka et al. [47]	Fodder maize (straw and chaff)	3–12 mm, 25–70 mm	Insertion into the rotation drum (dimension not specified), rotational speed: 14 rpm, time: 5 min	0.00–88.00%
Ivanova et al. [48]	Miscanthus, Giant Reed, Giant Knotweed, Hemp, Sweet Sorghum	3.8 mm, 8 mm,	EN 1510-2	74.40–97.70%
Nurek et al. [49]	Mixture of logging residues, including branches and needles from Scots Pine	0–1 mm, 1–4 mm, 4–8 mm, 8–16 mm	EN-ISO 17831-2:2016-02	42.00–72.50%
Ndindeng et al. [50]	Two types of rice residues	≥1 mm, 0.301–0.99 mm, ≤0.300 mm	The drop resistance test	No data
Chou et al. [51]	Rice bran, Soybean residue, Sawdust of *Acacia confusa*	10–5 mm, 5–2 mm, <2 mm, 250–450 µm	Taguchi method	No data
Wróbel et al. [52]	*Silphium perfoliatum* L.	10 mm, 6 mm	PN-EN 15210-2:2011	80.20–95.04%

The obtained research results are consistent with the majority of authors. Muntean et al. [46] tested hemp briquettes and obtained the highest mechanical strength for the smallest fraction. However, on the other hand, in the case of the remaining plant materials, the briquette made of the fraction with the lowest disintegration was the most susceptible to disintegration. Niedziółka et al. [47] noticed that briquettes made of fodder corn with finer crushing are characterized by a higher mechanical durability, at the level of 88%, similarly as in the current work (the value of 0% given in Table 2 was related to the experimental chaff briquette, which completely disintegrated). In a study by Ivanova et al. [48], the obtained values of the mechanical strength of briquettes were highly diversified but very similar to those obtained by the authors. The highest durability was recorded for the hemp briquette with the lowest degree of fragmentation. However, in other work, there were cases where briquettes made of a fraction similar to that in this study were characterized by a much lower mechanical durability index (Du = 42–72.5%) [49]. However, the researchers used a different fractional composition and different process temperatures to produce briquettes; therefore, the briquettes could not be properly densified. Chou [51], on the basis of the Tamagutchi method, found that the briquette made of the smallest fraction has the best properties.

The obtained results are also in line with the research performed by Ndindeng et al. [50] and Wróbel et al. [52], who observed that the briquettes durability increases with a decrease in material disintegration (agglomerated particle sizes). Other author report that smaller briquettes particles may result in a denser material structure [53]. The effectiveness of using the finest fractions for briquettes in terms of mechanical durability is also confirmed by other studies [17,26,27,54]. On the other hand, research studies are indicating that larger particle size results in a better durability of the briquette and other fuel quality parameters [30,31,55]. This issue is significant from a practical point of view as it influences the production process costs. Smaller particles allow for stronger structural bonds, but they require more energy input both during the biomass shredding and during the compaction (small particles absorb more energy exerted by the piston rod of the briquetting device) [25]. The decrease in the value of the mechanical durability of straw briquettes for greater fractions might be explained by the voids appearing between the particles in the compacted material. Schineberger [56] showed that a larger fraction of the material translates into an increase in the distance between the briquette particles. As a result of large distances, the interaction of particles decreases, the cohesion of the formed molecular bridges decreases, and the van der Waals force reduces as well.

3.3. The Mechanical Durability Index—The Influence of the Operation Time of the Working Chamber

As loose briquettes (without packaging) are very often transported over long distances (to deliver biomass to the heating units), their quality is important after prolonged exposure to vibration, friction, and impacts on walls of the trailer while driving. Therefore, such a test can be considered as an element of simulation of the possibility of mechanical degradation of briquettes transported over long distances or exposed to long-term warehouse and logistics processes. The results of the extended operation time of the working chamber are shown in Figure 3. Detailed data are included in Supplementary Materials Tables S1–S3.

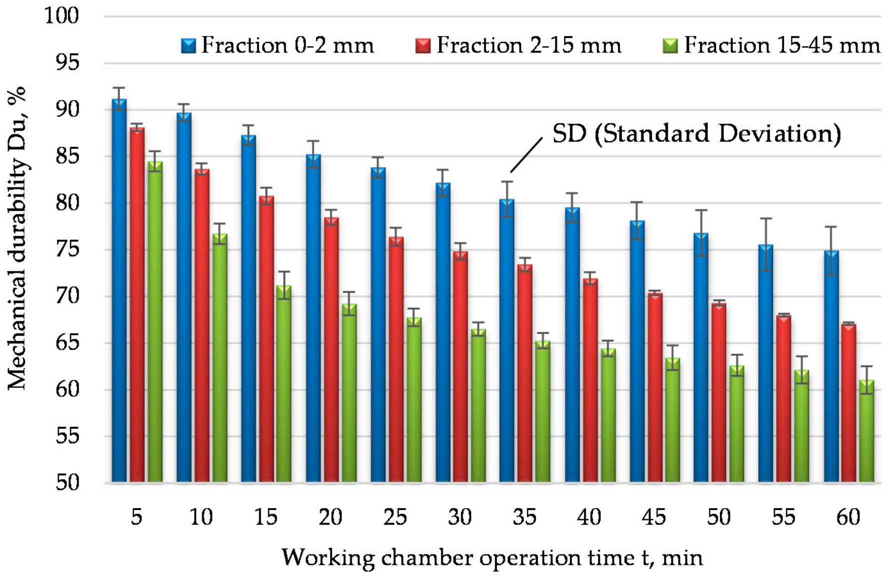


Figure 3. Influence of the working chamber operation time on mechanical durability of wheat straw briquettes (n_1 = 21 rpm).

The increase of the working chamber's operation time resulted in a gradual decrease in straw briquettes' mechanical durability for all investigated fractions. However, wheat straw briquettes made of the finest particles were distinguished by the lowest decrease in mechanical durability with the extended operation time of the working chamber.

For the 0–2 mm fraction, the mechanical durability of briquettes has changed from Du = 91.17% (operation time of the working chamber t_5 = 5 min) to Du = 74.91% (t_{60} = 60 min). In the case of a 2–15 mm fraction, the Du index varied from 88.12% (t_5 = 5 min) to 67.08% (t_{60} = 60 min). In turn, the mechanical durability of the briquettes compacted from the largest particles (15–45 mm fraction) was reduced from 84.48% (t_5 = 5 min) to 61.05% (t_{60} = 60 min). The reduction of the mechanical durability as a function of the working chamber operation time results mainly from the intense mutual friction of the briquettes and their impact against the hard surface of the chamber. Therefore, the extension of the briquette residence time in such conditions must increase the damage to the material and thus deteriorate its quality. Moreover, the tests revealed that briquettes made of a larger fraction had greater deterioration of their mechanical durability. Comparing the data obtained for the operation time of the working chamber t_5 and t_{60}, the difference in mechanical durability was as follows: ΔDu = 16.26% for the 0–2 mm fraction, ΔDu = 21.04% for the 2–15 mm fraction, and ΔDu = 23.43% for the 15–45 mm fraction, respectively. Thus, the fraction of the material in the briquetting process is crucial to obtain a good quality of the agglomerated product.

However, the decrease in this mechanical durability of briquettes was not linear (Figure 4). In order to better visualize the course of changes in the mechanical durability index of briquettes, the results were shown in the form of the difference between the theoretical value of the adopted Du index before the test (t_0 = 0 min, Du = 100%) and the obtained Du index value after a given test duration time. The results indicated that the initial increase in test duration (until ca. t_{20} = 20 min) caused a significant decrease in the mechanical durability of briquettes. However, further extension of the working chamber working time resulted in a gradual decrease in the difference in the value of the Du index. The difference between the Du index obtained at a given operation time of the working chamber and the previous one was decreasing. It can be assumed that the value of the mechanical durability index stabilized (the curves flatten out). It is confirmed by logarithmic trend lines whose degrees of matching R^2 are at an acceptable level (R^2 = 0.9066 for 0–2 mm fraction, R^2 = 0.8503 for the 2–15 mm fraction, and R^2 = 0.9569 for 15–45 mm fraction).

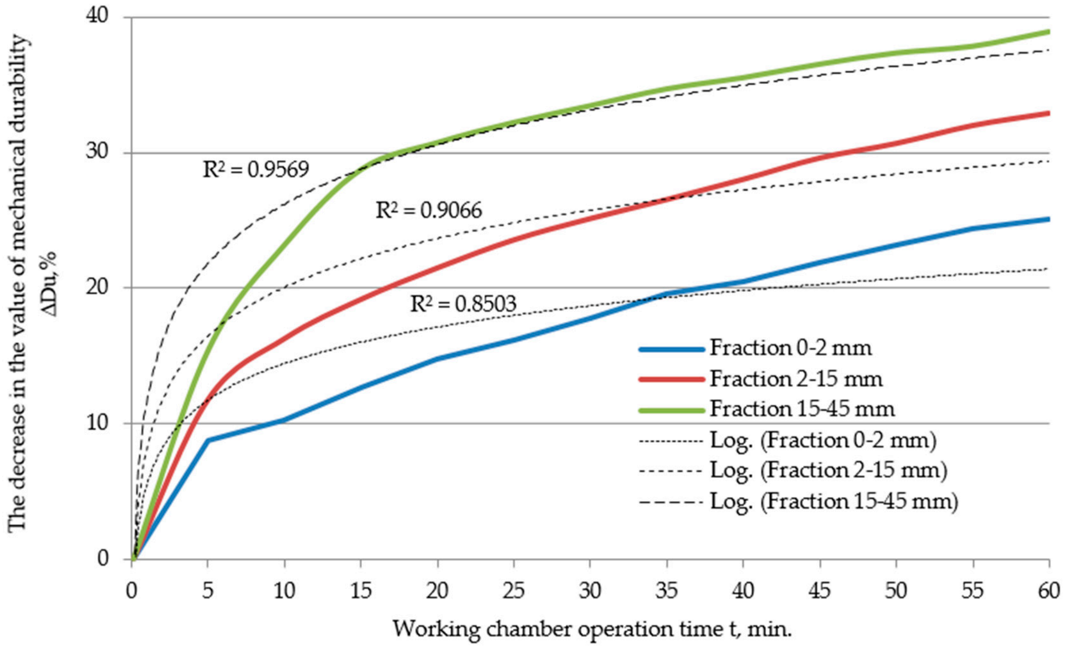


Figure 4. Decrease of mechanical durability Du as a function of working chamber operation time (n_1 = 21 rpm).

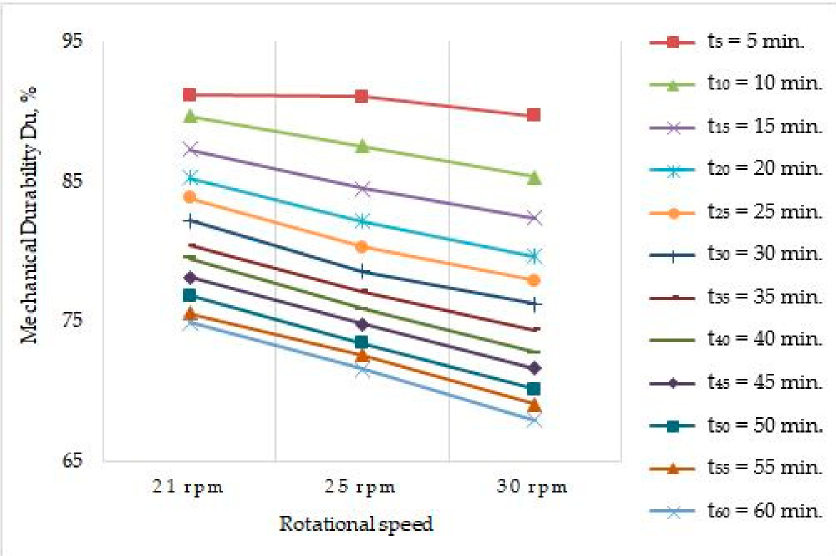
Several factors can explain the observed trend of the curve behavior and the stabilization effect of the mechanical durability index. The remarkable initial decrease in the mechanical durability of the briquette was due to the rapid smoothing of the sharp edges of the briquette as a result of the detachment of material particles in these places caused by its impact against the walls of the chamber and other briquettes. However, for a longer operation time of the working chamber, the cumulated amount of material particles separating from the briquette decreases. It arises from the fact that due to the pressure forming of the briquette in the matrix, the internal particles are better bonded to each other than the particles from the external part of the briquette (they are better pressed/compacted). Consequently, it makes it more difficult to damage the briquette further. On the other hand, the present material particles in the working chamber can also create a damping layer and reduce the impact force of the briquettes against the hard walls. The more loose particles there are in the chamber, the greater the potential to limit the negative effects of bouncing briquettes. A similar phenomenon occurs in the acoustic examination of materials. As a result of mechanical impacts, the substrate deteriorates. In this way, the particles detach from it, damping the mechanical impact and consequently reducing the noise level [57].

3.4. The Mechanical Durability Index—The Influence of the Rotational Speed of the Working Chamber

An additional element of the analysis was to check the mechanical strength of briquettes for the parameters of the working chamber, exceeding the ISO standard. Although the PN-EN ISO 17831-2: 2016-02 standard specifies the conditions under which the durability of briquettes should be tested, they do not always correspond to long-term and real intense conditions to which the agglomerated material is subjected in practice. In situations where briquettes are particularly susceptible to damage (long transport, multi-stage loading and unloading processes, too long logistic and warehouse chain), it may lead to an unexpected decrease rate in mechanical durability. The results of the experiments performed for other rotational speeds of the working chamber are shown in Figure 5. Detailed data are included in Supplementary Materials Tables S1–S3.

As the rotational speed of the working chamber increased, the mechanical durability of the briquettes decreased, regardless of its operation time. For the 0–2 mm fraction, the mechanical durability of briquettes in the case of rotational speed n_1 = 21 rpm varied from Du = 91.17% (t_5 = 5 min) to Du = 74.91% (t_{60} = 60 min). The difference in durability was ΔDu = 16.26%. Increasing the rotational speed to n_2 = 25 rpm caused the range of the mechanical durability of the briquettes to change, and it ranged from Du = 91.06% (t_5 = 5 min) to Du = 71.60% (t_{60} = 60 min), which caused the difference in durability to increase and amounted to ΔDu = 19.46%. The increase in the difference in mechanical durability was also obtained for the highest setting of rotational speed n_3 = 30 rpm. After t_5 = 5 min, the value of Du amounted to 89.65%. The measurement of mechanical durability after t_{60} = 60 min was Du = 67.94%, which resulted in a durability difference ΔDu = 21.71%.

(**a**)



(**b**)

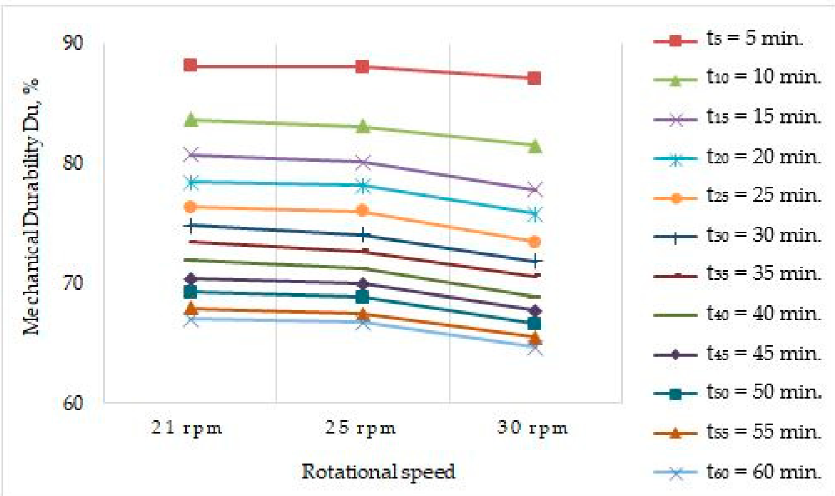


Figure 5. *Cont*.

(**c**)

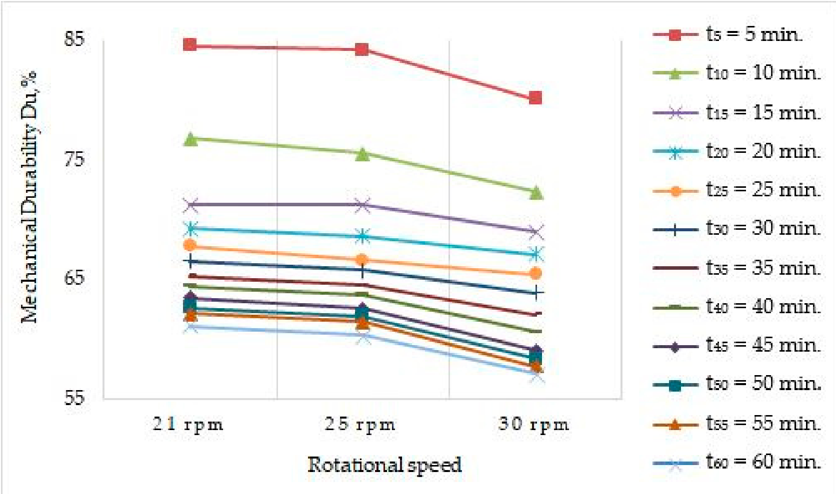


Figure 5. Influence of rotational speed of the working chamber on the mechanical durability Du of wheat straw briquettes: (**a**) fraction 0–2 mm; (**b**) fraction 2–15 mm; (**c**) fraction 15–45 mm.

In the case of a 2–15 mm fraction, the results indicated the same trend. For the rotational speed n_1 = 21 rpm, n_2 = 25 rpm, and n_3 = 30 rpm, the difference in the value of the mechanical durability index Du between the operation time of working chamber t_5 = 5 min and t_{60} = 60 min amounted to ΔDu = 21.04%, ΔDu = 21.34%, and ΔDu = 22.43%, respectively. It can be observed that for higher rotational speeds, the mechanical durability index Du deteriorates.

A similar relationship was found for the 15–45 mm fraction as well. The mechanical durability index reduced from Du = 84.48% (n_1 = 21 rpm, t_5 = 5 min) to Du = 80.02% (n_1 = 30 rpm, t_5 = 5 min). While for the t_{60} = 60 min, the mechanical durability index changed from Du = 61.05% (n_1 = 21 rpm) to Du = 57.09% (n_1 = 30 rpm).

Such a behaviour is a result of the greater number of rotations of the working chamber, causing the increase of the number of strokes of the briquettes against the walls and finally higher losses of mass. Thus, the longer operation time of the working chamber, the greater the number of strokes of the briquettes and the deterioration of its quality. Interestingly, for the larger fraction of the biomass particles (15–45 mm), the change in the Du value was significantly greater in comparison to the briquettes made of the finer fraction (0–2 mm). Based on this observation, it can be concluded that the briquettes compacted from a larger fraction should not be transported over long distances or subjected to too much complex/numerous logistics operation in comparison to briquettes made of a fine fraction. It should be taken into account during the production process of briquettes as it enables selecting the proper settings of the mill.

3.5. Main Results of Statistical Analysis

The statistical analysis (applying two-way analysis of variance ANOVA) confirmed that there is a strong dependence between the working chamber operation time (t) and the mechanical durability index of briquettes. Likewise, changing the rotational speed (n) of the working chamber significantly affects the mechanical durability as well.

In terms of combining of these two parameters (n·t), no significance was observed for the briquettes made of 0–2 mm fraction. However, in case of the 2–15 mm and 15–45 mm fractions, the interaction for these parameters (n·t) was still significant. This is due to the higher durability of the briquette made of fine material particles, which is less susceptible to the influence of the analyzed external factors. Briquettes from a thicker fraction are characterized by lower durability; hence, the influence of two harmful factors favors the further deterioration of their properties. Detailed data of the analysis of variance are presented in Table 4.

Table 4. Results of analysis of variance (two-way ANOVA) for the dependent variable (Du index).

Effect	SS	df	MS	F	*p*
For the 0–2 mm fraction					
Intercept	511,905.5	1	511,905.5	250,465.9	0.000000
Rotational speed of the working chamber (n)	4731.9	12	394.3	192.9	0.000000
Working chamber operation time (t)	446.5	2	223.2	109.2	0.000000
Interaction (n·t)	75.5	24	3.1	1.5	0.112650
Error	79.7	39	2.0		
For the 2–15 mm fraction					
Intercept	453,629.6	1	453,629.6	2,734,809	0.000000
Rotational speed of the working chamber (n)	95.3	2	47.6	287	0.000000
Working chamber operation time (t)	6631.6	12	552.6	3332	0.000000
Interaction (n·t)	13.3	24	0.6	3	0.000413
Error	6.5	39	0.2		
For the 15–45 mm fraction					
Intercept	373,089.7	1	373,089.7	632,796.2	0.000000
Rotational speed of the working chamber (n)	179.4	2	89.7	152.1	0.000000
Working chamber operation time (t)	9347.2	12	778.9	1321.1	0.000000
Interaction (n·t)	28.7	24	1.2	2.0	0.024200
Error	23.0	39	0.6		

SS—value of variability (sum of squares of all deviations), df—degree of freedom, MS—mean square (variance value), F—value of F-statistic, *p*—probability value.

4. Conclusions

The mechanical durability of briquettes is considered as the most important quality parameter. Due to the often extended process of fuel delivery to the end user (multi-stage logistic chain, long transportation distance), briquettes are exposed to damage related to crushing, dusting, or cracks. Therefore, it is important to provide a durable fuel that is resistant to degradation of external factors. Both briquettes and other compacted forms of biomass should be characterized by a high index of mechanical durability, because it guarantees their efficient utilization, especially in energy purposes.

The purpose of this study was to investigate the effect of wheat straw particles comminution on the mechanical durability index of briquettes. The research was performed in a wider range of operating conditions than are defined in the ISO standard.

The fragmentation of the material significantly influenced the mechanical durability index. The value of this index was the highest for the smallest fraction (0–2 mm) and amounted to Du = 91.17% according to the PN-EN ISO 17831-2: 2016-02 standard. The briquettes made of larger particles were characterized by lower mechanical durability. The operation time of the working chamber also resulted in lowering of the mechanical durability, regardless of the fraction of the material. However, the larger fraction of briquettes was investigated, and a greater difference in Du between the results obtained for t_5 = 5 min and t_{60} = 60 min was observed. A similar trend was detected in the case of a rotational speed increase of the working chamber. Testing the mechanical durability of briquettes under the increased rotational speed of the working chamber is important from a practical point of view. Weight losses due to mechanical damage due to long-distance transportation are difficult to estimate. Due to the fact that there are not such simulations that could determine the decrease in the mechanical durability of briquettes under such conditions, the results of this work provide some new data on this subject. Namely, in practice, fine fraction briquettes can be transported over longer distances, and their degradation degree should be lower. In turn, in case of briquettes made of larger fractions, the logistics chain should be minimized to maintain the acceptable level of fuel quality by the final user. It can be conclude also that it possible to save some energy during the biomass milling process (thicker fraction is obtained) but as a consequence for these briquettes, both the logistic chain and the transportation distance should be reduced.

These tests leave a space for further research, such as the optimization of the material fraction in terms of shredding costs and mechanical durability, or determination of the partial material losses during the complete logistic chain of briquettes handling.

Supplementary Materials: The following are available online at http://www.mdpi.com/1996-1073/13/23/6186/s1, Table S1. Mechanical durability of wheat straw briquettes produced of 0–2 mm fraction depending on the working chamber operation time and the rotational speed of the working chamber, Table S2. Mechanical durability of wheat straw briquettes produced of 2–15 mm fraction depending on the working chamber operation time and the rotational speed of the working chamber, Table S3. Mechanical durability of wheat straw briquettes produced of 15–45 mm fraction depending on the working chamber operation time and the rotational speed of the working chamber.

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