



EFFECTS OF LENGTH ON MECHANICAL DURABILITY OF VARIOUS WOOD PELLETS

Author(s):R.C Akdeniz¹ – O. Esmer²**Affiliation:**¹Ege University, Faculty of Agriculture, Department of Machinery and Technologies Engineering, Bornova/Izmir, 35100, Turkey²Ege University, Graduate School of Natural and Applied Science Institute, Agricultural Machinery and Technologies Engineering, MSc, Bornova/Izmir, 35100, Turkey**Email address:**

rcakdeniz87@gmail.com, ogulcanesmer@gmail.com

Abstract

In this study, an investigation was made of the effect of length on the mechanical durability of pellets made from Valonia Oak industrial waste, Calabrian Pine residue and sawdust at various mixture ratios of these materials. The pellets were classified into six length classes of $3.15 \text{ mm} < \text{PL} \leq 20 \text{ mm}$, $20 \text{ mm} < \text{PL} \leq 35 \text{ mm}$, $35 \text{ mm} < \text{PL} \leq 38 \text{ mm}$, $38 \text{ mm} < \text{PL} \leq 40 \text{ mm}$, $40 \text{ mm} < \text{PL} \leq 45 \text{ mm}$ and $45 \text{ mm} < \text{PL}$, and each length class was classified into four categories (C-I, C-II, C-III and C-IV) according to surface cracks. Mechanical durability test results showed that, in the 66.5-33.5% acorn-pine mixture ratio, only the $20 \text{ mm} < \text{PL} \leq 35 \text{ mm}$ -C-I pellets met the 97.5% mechanical durability limit of ENplus, but most of the other classes met the minimum PFI standard mechanical durability limit of 95%.

In the free fall tests, all length classes showed the same results for C-I pellets: these did not break into pieces easily, whereas C-IV pellets broke into pieces at the first fall. Also, their weight loss was greater than that of the other categories.

Keywords

wood pellet, forest residue, valonia waste, length, mechanical durability

1. Introduction

Turkey has approximately 22 342 000 ha of forest, of which 5 886 195 ha or 26.34% is oak, and 5 610 215 ha or 25.11% is Calabrian pine [1]. These tree species

are widely used in the timber industry, especially in furniture making [2]. Also, acorns are used as a raw material in the leather industry in the tanning process [3] and in the animal feed industry [4] [5].

It is estimated that the sawdust and other wastes from the processing of these and other tree species, together with the branches, shoots and other pruned materials have an energy value of 859 899 TOE according to BEPA data. The min-max oven-dry calorific values of oak and pine are 3972-4287 cal/gr and 4216-4531 cal/gr [6] respectively, so that these materials could be used as an important source in the production of heat energy.

Because of its dispersed state and various other physical characteristics, this biomass must undergo some pre-treatment in order to convert it into a productive form. Pelletizing technologies are widely applied in order to increase the energy density of biomass and to reduce the costs of storage and transport [7]. In order for pellets to be easily transported and to have a long shelf life, it is necessary to set up standard accepted mechanical durability values for pellets [8].

In this study, an investigation was made of the mechanical durability of pellets made at a factory producing valonia from acorns, using the waste from the valonia production process (Figure 1), [9] mixed at a proportion of 60-81% [3] with Calabrian pine forest residue and sawdust. These pellets are used to meet the heating needs of the factory itself and some are sold commercially. The effect of cracks on the pellet surface was also investigated, separating the pellets into length classes.



Figure 1. Valonia production process

2. Materials and Methods

Materials

Raw Materials

Pine forest residue, industrial waste from the acorn industry and sawdust waste from the furniture industry were used (Figure 2). The pine residue contained 10.14% moisture, the acorn waste 40.59%, and the sawdust 10.92%. The acorn waste was spread on the ground and dried naturally, reducing moisture content to a value of 28.56%.



Figure 2. Raw Materials

Pellets

The pellets used in the study were from a biomass mixture consisting of 66.5-33.5% acorn-pine and 50-25-25% acorn-pine-sawdust. Granule size was

reduced in a hammer mill, and the pellets were produced in a disc-type pelletizing machine with a capacity of 1000 kg/h and holes of 8 mm diameter, and cooled naturally (Figure 3).



Figure 3. Pelletizing machine with 8 mm disc and pellets

Devices and Equipment

A drying oven (a) was used in moisture analysis of the pellets, digital calipers (b) with an accuracy of 0.001 to measure length and diameter, a scale (c) with an accuracy of 0.001 to measure weight, a durability tester (d) and sieves (e) to determine mechanical

durability, a steel plate (f) as the surface on which the pellets fell in free fall tests, a digital microscope (g) with a five megapixel sensor, adjustable polarizer, up to 200x magnification depending on working distance, and a resolution of 2592x1944 to photograph cracks. Sample containers (h) were used in all analyses (Figure 4).



Figure 4. Devices and Equipment

2.2. Methods

Moisture Analysis

Samples of at least 50 g were weighed with five iterations on a sensitive scale and dried in a drying oven at a temperature of 105°C for 24 hours. Moisture values were calculated on the basis of wet weight (MWb) by Equation 1, and on the basis of dry weight (MDb) by Equation 2 [10].

$$M_{Wb}(\%) = \frac{W_{fi} - W_f}{W_{dry\ sample} + W_{water}} \times 100 \quad (1)$$

$$M_{Db}(\%) = \frac{W_{fi} - W_f}{W_{dry\ sample}} \times 100 \quad (g) \quad (2)$$

W_{fi} = First Weight of Sample and Container (g)

W_f = Final Weight of Sample and Container (g)

$$W_{water} = W_{fi} - W_f \quad (g)$$

$$W_{dry\ sample} = W_{fi} - W_{container} - W_{water} \quad (g)$$

Distribution of Pellets by Size

Pellet lengths (PL) of each mixture were separated into six classes of $3.15\text{ mm} < PL \leq 20\text{ mm}$, $20\text{ mm} < PL \leq 35\text{ mm}$, $35\text{ mm} < PL \leq 38\text{ mm}$, $38\text{ mm} < PL \leq 40\text{ mm}$, $40\text{ mm} < PL \leq 45\text{ mm}$, $45\text{ mm} < PL$, and percentage distributions of the length classes were calculated according to weight and number. The original length class designations were written in the text but were named in the tables as follows:

$$-3.15\text{ mm} < PL \leq 20\text{ mm} = PL1$$

$$-20\text{ mm} < PL \leq 35\text{ mm} = PL2$$

$$-35\text{ mm} < PL \leq 38\text{ mm} = PL3$$

$$-38\text{ mm} < PL \leq 40\text{ mm} = PL4$$

$$-40\text{ mm} < PL \leq 45\text{ mm} = PL5$$

$$-45\text{ mm} < PL = PL6$$

It was determined that in general, pellets produced on the market have a length of 3-4 times their diameter [11], and so the ideal length of pellets produced with an 8 mm disc would be $20\text{ mm} < PL \leq 35\text{ mm}$. Maximum pellet length is 38.1 mm according to the PFI standard [12] and 40 mm according to the ENplus standard [13]. The proportion of pellets accepted longer than the maximum pellet length is 1% for the two standards, while according to the ENplus standard [13], pellets longer than 45 mm are not accepted at all. Therefore, the length classes of $35\text{ mm} < PL \leq 38\text{ mm}$, $38\text{ mm} < PL \leq 40\text{ mm}$ and $45\text{ mm} < PL$ were selected. Also, because pellets with a granule size of less than 3.15 mm are classed by the PFI [12] and ENplus [13] standards as dust, the proportion by weight of dust was calculated with the help of a 3.15 mm sieve.

Distribution of Length Classes by Crack Categories

The pellets were examined under four categories, C-I, C-II, C-III and C-IV, according to the cracks on their surfaces.

The categories were defined as follows:

–C-I: No visible cracks on the surface

- C-II: At most two cracks on the surface in the form of scratches or slightly deepened
- C-III: More than two surface cracks in the form of scratches, or deep
- C-IV: Shape changed by cracks; pellets about to break up (Figure 5).

Because pellets in the $3.15 \text{ mm} < \text{PL} \leq 20 \text{ mm}$ length group were too short, pellets in this group were not examined for division into crack categories.

The distribution of crack categories was calculated within each length class and as a percentage of all samples.

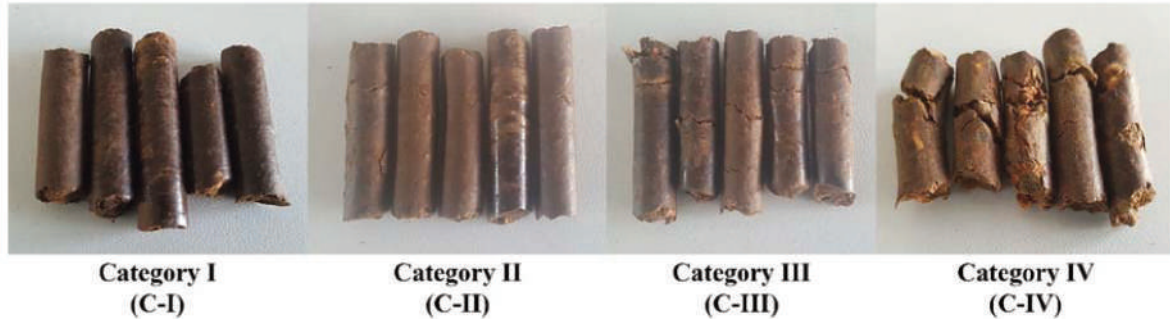


Figure 5. Crack Categories

Length – Diameter – Weight Measurements

The length (mm), diameter (mm) and weight (g) of 100 selected pellets was measured, and the maximum, minimum, mean and standard deviation were found.

Mechanical Durability by Length and Crack Categories

Test with a Pellet Durability Tester

The testing stages were as follows:

- Pellet sample were taken $500 \text{ g} \pm 10 \text{ g}$ in accordance with the ASAE S269.5 standard and weighed after removal of dust. This was recorded as the Pellet Sample Weight (PSW).
- The tester was operated for 10 minutes at $50 \pm 2 \text{ rpm}$.
- The samples were removed from the tester, and in accordance with the ASAE S269.5 standard [15], the broken pellet pieces and dust were separated from the sample using a 6 mm and 3,15 mm sieve, and weighed. Their weight was then recorded as the Pellet Final Weight (PFW).
- Pellet Durability (PD) was calculated using Equation 3, which showed the relationship between the variable PSW (the mass of the pellet pieces before tumbling) and the variable PFW (the mass of the pellet pieces after tumbling) [14].

$$(PD) = \frac{PSW(g)}{PFW(g)} \times 100 (\%) \quad (3)$$

Free Fall Tests

Pellets of each length class and crack category were allowed to fall freely from a height of 1.85 m, with

five iterations. The number of falls after which the pellet broke up was observed, and weight losses were calculated by weighing on a sensitive scale.

Photographs of Cracks

Photographs of the cracks taken with a digital microscope (Figure 4) were used to show the differences between the crack categories according to the surface cracks.

3. Results & Discussion

Results

Moisture Analysis

It was found that the average moisture on a wet and dry weight basis was 14.16% and 16.49% for 66.5-33.5% acorn-pine mixture ratio pellets, and 14.30% and 16.69% for 50-25-25% acorn-pine-sawdust mixture ratio pellets. The moisture of both samples was above the 10% maximum on a wet weight basis of the PFI [12] and ENplus [13] standards.

Distribution of Pellets by Size

Pellets of neither mixture accorded with the PFI standard, which states that the proportion of pellets exceeding the maximum pellet length of 38.1 mm should be 1% [12]. In the case of the acorn-pine mix, the total proportion of pellets longer than 38 mm was 13.55%, while for the acorn-pine-sawdust mix this figure was found to be 7.76%. According to the ENplus standard, the maximum pellet length is 40 mm, and at most 1% of pellets must be in the $40 \text{ mm} < \text{PL} \leq 45 \text{ mm}$ class [13]. The $45 \text{ mm} < \text{PL}$ class is

not accepted [13]. It was determined that the mixtures did not conform to these standards.

According to both standards, pieces smaller than 3.15 mm are counted as dust [12], [13]. The amount

of dust in both mixtures was below the maximum proportion of 1%.

Table 1. Distribution of Pellet Length Classes by Number and Weight

Pellet Type 1: 66.5-33.5% Acorn-Pine Mixture Ratio					
Length Class	No	%	Distribution in 100 pellets	Weight (g)	%
PL1	1676	39.21	39	1187.00	21.26
PL2	1799	42.09	42	2589.66	46.38
PL3	220	5.15	5	431.78	7.73
PL4	132	3.09	3	273.13	4.89
PL5	277	6.48	7	637.37	11.42
PL6	170	3.98	4	439.85	7.88
Total	4274	100.00	100	5558.79	99.56
			Fines (g)	24.78	0.44
			Total (g)	5583.57	100
Pellet Type 2: 50-25-25% Acorn-Pine-Sawdust Mixture Ratio					
Length Class	No	%	Distribution in 100 pellets	Weight (g)	%
PL1	2206	49.91	50	1474.23	31.11
PL2	1749	39.57	40	2209.56	46.63
PL3	122	2.76	3	223.14	4.71
PL4	64	1.45	1	126.85	2.68
PL5	141	3.19	3	307.39	6.49
PL6	138	3.12	3	353.72	7.47
Total	4420	100	100	4694.89	99.09
			Fines (g)	43.34	0.91
			Total (g)	4738.23	100

Table 2. Distribution of Each Length Class by Crack Categories

Length Class		Pellet Type 1					Pellet Type 2				
		Crack Categories				Total	Crack Categories				Total
		I	II	III	IV		I	II	III	IV	
PL2	No	614	921	257	7	1799	459	986	285	19	1749
	%	34.13	51.20	14.29	0.38	100	26.24	56.38	16.30	1.08	100
PL3	No	64	129	25	2	220	31	75	14	2	122
	%	29.09	58.64	11.36	0.91	100	25.41	61.48	11.48	1.63	100
PL4	No	24	83	22	3	132	15	41	7	1	64
	%	18.18	62.88	16.67	2.27	100	23.44	64.06	10.94	1.56	100
PL5	No	93	152	28	4	277	31	89	15	6	141
	%	33.58	54.87	10.11	1.44	100	21.99	63.12	10.64	4.26	100
PL6	No	68	75	24	3	170	44	83	11	0	138
	%	40.00	44.12	14.12	1.76	100	31.89	60.14	7.97	0.00	100
Note: The 3.15 mm < PL ≤ 20 (PL1) class was not separated into crack categories.											

Distribution of Length Classes by Crack Categories

Distribution of Each Length Class

Table 2 shows the numerical and percentage distributions of crack categories within each length class of pellet. It can be seen from this that in the length classes of both mixture types, there were more pellets in C-II than in the other crack categories. In

66.5-33.5% of acorn-pine-sawdust mixture ratio pellets, C-II, C-III and C-IV cracks were found most in the 38 mm < PL ≤ 40 mm class.

In 50-25-25% of acorn-pine-sawdust mixture ratio pellets, there were fewer in the C-III crack category as size increased, but the number in the C-I category also decreased apart from in class 45 mm < PL. Most C-IV cracks was found in class 40 mm < PL ≤ 45. In

each mixture, most C-I cracks was found in class 45 mm < PL.

Distribution in the Whole Pellet Sample

The first five rows in Table 3, which are arranged according to crack categories in both mixtures apart from the 3.15 mm < PL ≤ 20 mm class, were the same for both mixture ratios. For all samples, the length class 20 mm < PL ≤ 35 mm and C-II cracks were the most frequent. It was calculated that in the 66.5-33.5% acorn-pine mixture pellets, the proportions of

C-I, C-II, C-III and C-IV cracks were 20.2%, 31.83%, 8.32% and 0.44% respectively, while they were 13.12%, 28.83%, 7.52% and 0.64% for the 50-25-25% acorn-pine-sawdust mixture.

The increase from C-I cracks to C-II cracks reduces mechanical durability. C-III cracks is not preferable for high mechanical durability, but also, C-IV cracks are definitely not desirable. Pellet durability will decrease because of this length class which was calculated in the acorn-pine mixture and the acorn-pine-sawdust mixture respectively as 39.21% and 49.91%.

Table 3. Distribution of Length Classes by Crack Categories in the Whole Pellet Sample and 66.5-33.5% Acorn-Pine and 50-25-25% Acorn-Pine-Sawdust Mixture Ratios

Series	Pellet Type 1		Pellet Type 2	
	%	Length Class and Crack Category	%	Length Class and Crack Category
1	39.21	PL1, C-I,II,III,IV	49.91	PL1, C-I,II,III,IV
2	21.56	PL2, C-II	22.31	PL2, C-II
3	14.37	PL2, C-I	10.38	PL2, C-I
4	6.01	PL2, C-III	6.45	PL2, C-III
5	3.56	PL5, C-II	2.01	PL5, C-II
6	3.02	PL3, C-II	1.88	PL6, C-II
7	2.18	PL5, C-I	1.70	PL3, C-II
8	1.94	PL4, C-II	1.00	PL6, C-I
9	1.75	PL6, C-II	0.93	PL4, C-II
10	1.59	PL6, C-I	0.70	PL3, C-I
11	1.50	PL3, C-I	0.70	PL5, C-I
12	0.66	PL5, C-III	0.43	PL2, C-IV
13	0.58	PL3, C-III	0.34	PL4, C-I
14	0.56	PL4, C-I	0.34	PL5, C-III
15	0.56	PL6, C-III	0.32	PL3, C-III
16	0.51	PL4, C-III	0.25	PL6, C-III
17	0.16	PL2, C-IV	0.16	PL4, C-III
18	0.09	PL5, C-IV	0.14	PL5, C-IV
19	0.07	PL4, C-IV	0.05	PL3, C-IV
20	0.07	PL6, C-IV	0.02	PL4, C-IV
21	0.05	PL3, C-IV	0.00	PL6, C-IV
	100	Total	100	Total

Length – Diameter – Weight Measurements

For 66.5-33.5% acorn-pine mixture ratio pellets, the following measurements were found: length (mm), maximum 50.15, minimum 12.14, mean 25.80, standard deviation 9.44; diameter (mm), maximum 8.10, minimum 7.62, mean 7.84, standard deviation 0.12; weight (g), maximum 2.82, minimum 0.57, mean 1.35, standard deviation 0.53, while for the acorn-pine-sawdust pellets, the measurements were length (mm), maximum 53.89, minimum 8.57, mean 21.90, standard deviation 9.28; diameter (mm), maximum 8.29, min 7.52, mean 7.92, standard deviation 0.17;

weight (g), maximum 2.92, minimum 0.40, mean 1.09, standard deviation 0.52.

Deviations in pellet diameter were greater in the 50-25-25% acorn-pine-sawdust pellets than in the 66.5-33.5% acorn-pine mixture ratio pellets.

Mechanical Durability by Length and Crack Categories

Pellet Durability Tester Results

The mechanical durability test results showed that, with the 66.5-33.5% acorn-pine mixture ratio pellets, only the 20 mm < PL ≤ 35 mm-C-I pellets were within the 97.5% mechanical durability limit of the

ENplus Standard [13]; however, the other classes met the minimum PFI standard [12] mechanical durability limit of 95% except for 3.15 mm < PL ≤ 20 mm-all cracks and 20 mm < PL ≤ 35 mm-C-III. With the 50-25-25% acorn-pine-sawdust mixture ratio pellets, none of the pellet classes were within the mechanical durability limit of the ENplus Standard, and only the 20 mm < PL ≤ 35 mm-C-I, 20 mm < PL ≤ 35-all cracks, 40 mm < PL ≤ 45-all cracks and 45 mm < PL

mixed cracks classes were within the mechanical durability limit of the PFI standard (Table 4).

With both pellet mixtures, even though pellets of the ideal pellet group of 20 mm < PL ≤ 35 mm were a mixture of all crack categories, they met ENplus or PFI standards. However, when only crack categories C-II and C-III are considered, mechanical durability progressively falls.

Table 4. Mechanical Durability of Pellets

Pellet Type 1: 66.5-33.5% Acorn-Pine Mixture Ratio				
Length Classes and Crack Categories	Pellet Sample Weight Before Test (g)	Pellet Sample Weight After Test (g)	Weight Loss (g)	Mechanical Durability (%)
PL1,2,3,4,5,6 C-I,II,III,IV	502.70	481.74	20.96	**95.83
PL1 – C-I,II,III,IV	500.16	469.15	31.01	*93.80
PL2 – CI	500.39	489.92	10.47	***97.91
PL2 – C-II	500.11	483.99	16.12	**96.78
PL2 – C-III	250.54	233.63	16.91	*93.25
PL2 – C-I,II,III,IV	500.50	487.44	13.06	**97.39
PL3 – C-I,II,III,IV	350.77	339.55	11.22	**96.80
PL4 – C-I,II,III,IV	220.40	210.26	10.14	**95.40
PL5 – C-I,II,III,IV	500.07	485.72	14.35	**97.13
PL6 – C-I,II,III,IV	375.67	361.78	13.89	**96.30
Pellet Type 2: 50-25-25% Acorn-Pine-Sawdust Mixture Ratio				
PL1,2,3,4,5,6 C-I,II,III,IV	500.91	471.16	29.75	*94.06
PL1 – C-I,II,III,IV	500.38	462.36	38.02	*92.40
PL2 – CI	364.43	352.68	11.75	**96.78
PL2 – C-II	500.59	472.35	28.24	*94.36
PL2 – C-III	200.61	185.72	14.89	*92.58
PL2 – C-I,II,III,IV	500.49	476.99	23.50	**95.30
PL3 – C-I,II,III,IV	168.04	159.54	8.50	*94.94
PL4 – C-I,II,III,IV	106.63	100.18	6.45	*93.95
PL5 – C-I,II,III,IV	243.43	227.27	16.16	*93.36
PL6 – C-I,II,III,IV	282.49	268.38	14.11	**95.01
***Pellets met the ENplus (EU) standard mechanical durability limit of 97.5%				
**Pellets met the minimum PFI (American) standard mechanical durability limit of 95%				
* Mechanical durability of pellets was lower than 95%				

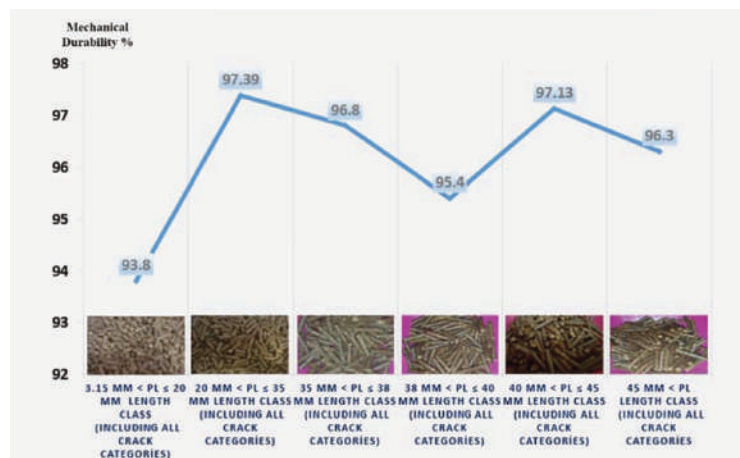


Figure 6. 66.5-33.5% Acorn-Pine Mixture Ratio Pellet Mechanical Durability by Length Classes

Some samples were found to be under 500 g. In these samples it was expected that the PDI value determined by the durability tester would be somewhat higher [15].

According to Figures 6 and 7, in which the mechanical durability of pellet lengths was examined against all crack categories, general mechanical durability fell with both mixtures between the length classes $20 \text{ mm} < \text{PL} \leq 35 \text{ mm}$ and $38 \text{ mm} < \text{PL} \leq 40$

mm. However, the lowest mechanical durability in both mixtures was found in the length class $20 \text{ mm} < \text{PL} \leq 35 \text{ mm}$. This is thought to arise from the large number of cracks in small pellets. Generally, it was found that the durability of 66.5-33.5% mixture pellets was higher than that of 50-25-25% mixture pellets. Adding sawdust to the pellet mixture had a negative effect on mechanical durability.

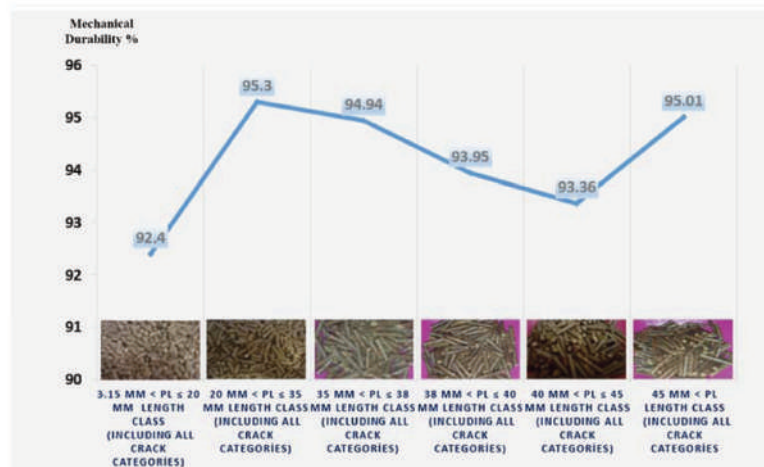


Figure 7. 50-25-25% Acorn-Pine-Sawdust Mixture Ratio Pellet Mechanical Durability by Length Classes

Free Fall Test Results

Three pellets were to be taken from each of the six length classes and crack categories, so that a total of 72 pellets were to be examined from each mixture. However, pellets of the class $3.15 \text{ mm} < \text{PL} \leq 20 \text{ mm}$ was not separated into crack categories, there were few or no examples of C-IV cracks, and some of pellets had been used in the mechanical durability tests, and so as a result of that 52 samples of 66.5-33.5% acorn-pine mixture ratio pellets and 50 of the 50-25-25% acorn-pine-sawdust mixture ratio pellets were examined.

According the results, all length classes generally showed the same results for the two types of pellet mixes, namely that C-I pellets did not break into pieces easily, fragmentation and loss of weight of C-II and C-III pellets was greater than that of C-I, and C-IV pellets broke into pieces at the first fall and their loss of weight was determined as higher than the other categories. $3.15 \text{ mm} < \text{PL} \leq 20 \text{ mm}$ class did not break into pieces because of their short length, but their mechanical durability was calculated to be the lowest in the durability tester results as shown in Table 4. Breaking and weight loss increased with increase in length. In general, longer pellets began to break from the end. (Figure 8). Breaking into four pieces was most commonly seen in 50-25-25% acorn-

pine-sawdust mixture ratio pellets of the $40 \text{ mm} < \text{PL} \leq 45 \text{ mm}$ length class (Figure 9).



Figure 8. Longer pellets beginning to break from the end



Figure 9. 50-25-25% Acorn-Pine-Sawdust mixture ratio $40 \text{ mm} < \text{PL} \leq 45 \text{ mm}$ Length Class Pellet

It was calculated from the results of the free fall test when 66.5-33.5% oak-pine mixture ratio pellets of the C-I crack category, which had shown the best mechanical durability, were examined by length class, that weight loss was 0.023 g in the $20 \text{ mm} < \text{PL} \leq 35$ class, 0.037 g in the $35 \text{ mm} < \text{PL} \leq 38$ class, 0.043 g in the $38 \text{ mm} < \text{PL} \leq 40$ class, and 0.050 g in the $40 \text{ mm} < \text{PL} \leq 45$ and $45 \text{ mm} < \text{PL}$ classes. In the 20 mm

< PL ≤ 35 class, only one pellet broke up; as length increased pellets broke into two, and in the 45 mm < PL class, some pellets were seen to break into three pieces (Table 5).

Table 5. 66.5-33.5% Acorn-Pine Mixture Ratio Pellets: Free Fall Test Results of C-I Cracks by Length

20 mm < PL ≤ 35 C-I												
Pellet No	Before st 1 Fall (g)	After st 1 Fall (g)	After nd 2 Fall (g)		After rd 3 Fall (g)		After th 4 Fall (g)		After th 5 Fall (g)		Total Weight Loss (g)	Pieces
1	1.46	-	-		-		-		1.44		0.02	1
2	1.17	-	-		-		-		1.15		0.02	1
3	1.39	-	-		-		-		0.72	0.64	0.03	2
35 mm < PL ≤ 38 C-I												
1	1.90	-	1.21	0.69	-	-	-	-	1.20	0.67	0.03	2
2	1.96	-	1.05	9.90	-	-	-	-	1.02	0.89	0.05	2
3	1.91	-	-		-		-		0.90	0.98	0.03	2
38 mm < PL ≤ 40 C-I												
1	2.06		1.40	0.63	-	-	-	-	1.38	0.62	0.06	2
2	2.02	-	-		-		-		1.05	0.94	0.03	2
3	1.94				0.89	1.03	-	-	0.88	1.02	0.04	2
40 mm < PL ≤ 45 C-I												
1	2.25	-	1.57	0.64	-	-	-	-	1.56	0.63	0.06	2
2	2.28	-	-		1.35	0.90	-	-	1.34	0.90	0.04	2
3	2.21	-	1.06	1.12	-	-	-	-	1.05	1.11	0.05	2
45 mm < PL C-I												
1	2.55	-	-		1.88	0.65	-	-	1.87	0.64	0.04	2
2	2.35	-	-		1.73	0.62	-	-	1.05	0.63	0.61	3
3	2.60	-	-		1.75	0.84	-	-	1.18	0.54	0.83	3
Pellets were weighed after each free fall, but the table shows only the weight when a pellet broke, and the final weight. Lines indicate that there was no change.												

Crack Photographs

As seen in Figure 10, cracks on the surface of pellets increased in size from C-II to C-IV. An increase in

pellet storage time or storage in unsuitable conditions increased deterioration, and cracks became progressively larger [16].

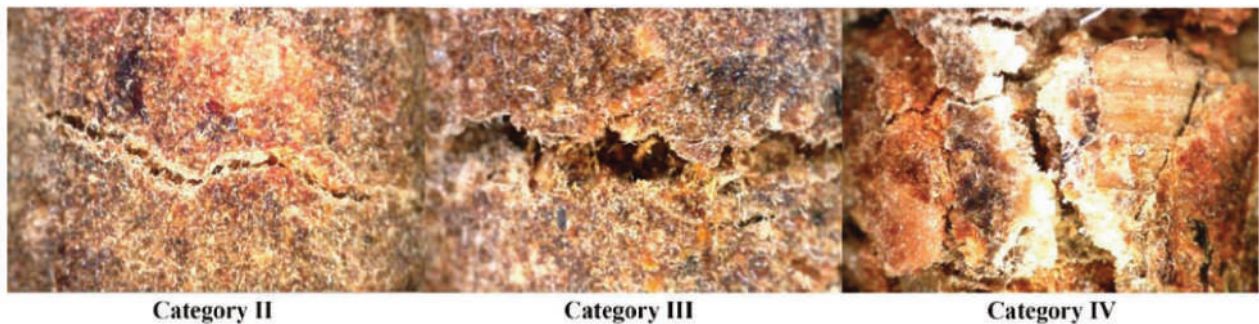


Figure 10. Photos of crack categories taken by digital microscope

4. Conclusions

Mechanical durability has great importance for pellet quality under market conditions, and there are many factors such as raw material properties, moisture content, pellet length and surface cracks which affect the mechanical durability of pellets.

Generally, if the length of pellets increases, the mechanical durability decreases, but pellet length and surface cracks should be investigated together. Even if the ideal pellet length shows high mechanical durability, mechanical durability will decrease as a result of an increasing percentage of C-III and C-IV cracks.

The shortest pellets showed low mechanical durability. In our opinion, pellets in this group are parts of longer ones. Also, some of the longer pellets showed high mechanical durability according to durability test results, but they easily broke into pieces in the free fall tests. This indicates that the results of durability and free fall tests must be evaluated together.

Also, considering that longer pellets have a lower burning efficiency and have higher emission values [17], producers should adjust the cutting knives of their pelletizing machines according to the maximum length limits given in pellet standards.

References

- [1] **Turkish General Directorate of Forestry.:** 2015. Türkiye Orman Varlığı 2016-2017 [Forests in Turkey 2016-2017]. Republic of Turkey Ministry of Forestry and Water Management, pp. 36.
- [2] **Turkish General Directorate of Forestry.:** 2013. Orman Atlası [Forest Atlas]. Republic of Turkey Ministry of Forestry and Water Management, pp. 116.
- [3] **NIIR Board of Consultants & Engineers.:** 2011. Leather Processing & Tanning Technology Handbook, NIIR Project Consultancy Services, pp. 467. ISBN: 9788190568593
- [4] **Wickens G. E.:** 1995. Non-Wood Forest Products 5 Edible Nuts, Food And Agriculture Organization Of The United Nations, pp. 129. ISBN 92-5-103748-5
- [5] **Rosengarten, F. Jr.:** 2004. The Book of Edible Nuts. pp. 268. ISBN-10: 0486434990
- [6] **Erten A. P., Önal S.:** 1985. Ağaç Türlerimizin Odun ve Kabuklarının Değerlerinin Saptanmasına İlişkin Araştırmalar [Determination of Caloric Value of Native Species Woods and Barks]. Or. Araş. Ens. Dergisi, Temmuz, Vol. 31, No. 62, pp. 91-110.
- [7] **Garcia-Maraver A., Perez-Jimenez J. A., Zamorano M.:** 2015. Biomass Pelletization, Chapter 1, Background. pp. 2-20. ISBN 978-1-78466-062-8.
- [8] **Garcia-Maraver A., Carpio M.:** 2015. Biomass Pelletization, Chapter 2, Factors Affecting Pellet Quality. pp. 21-35, ISBN 978-1-78466-062-8
- [9] **Küçükyavuz O.:** 2002. Valeks İmalatı Sanayi Profili [Profile of the Valonia Production Industry]. T.C Sanayi Ve Ticaret Bakanlığı, Sanayi Araştırma ve Geliştirme Genel Müdürlüğü - [Republic of Turkey Ministry of Industry and Trade, General Directorate of Industry Research and Development], pp. 23.
- [10] **Govett R., Mace T., Bowe S.:** 2010. A Practical Guide For The Determination Of Moisture Content Of Woody Biomass, University of Wisconsin, pp. 20.
- [11] **Kofman P. D.:** 2007. Simple ways to check wood pellet quality, Processing/ Products No. 11, pp. 2.
- [12] **Pellet Fuels Institute.:** 2015. Pellet Fuels Institute Standard Specifications for Residential/Commercial Densified Fuel, July 9, 2015, pp. 10.
- [13] **European Pellet Council.:** 2015. ENplus Handbook, Part 3: Pellet Quality Requirements, European Pellet Council (EPC), Version 3.0, August 2015, pp. 10.
- [14] **ASABE.:** 2012. Densified Products for Bulk Handling — Definitions and Method. ASAE S269.5, October 2012.
- [15] **Stark C., Fahrenholz A.:** 2015. Evaluating Pellet Quality, Kansas State University Agricultural Experiment Station and Cooperative Extension Service, July 2015, Published Online: MF3228, pp. 4.
- [16] **Grahama S., Eastwick C., Colin Snape C., Quick W.:** 2017. Mechanical degradation of biomass wood pellets during long term stockpile storage. Fuel Processing Technology, Vol. 160, No. 1, pp. 143-151. <http://dx.doi.org/10.1016/j.fuproc.2017.02.017>
- [17] **Wöhler M., Jaeger D., Reichert G., Schmidl C., Pelz S. K.:** 2017. Influence of pellet length on performance of pellet room heaters under real life operation conditions. Renewable Energy, Vol. 105, pp. 66-75. <http://dx.doi.org/10.1016/j.renene.2016.12.047>