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Effect of Densification Conditions on Physical Properties of Pellets Made From Sawmill Residues

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ABSTRACT:*Sawmill residues produced in wood processing of Pilon (Hyeronimaalchorneoides) and Eucalyptus (Eucalyptus spp) species, were used to fabricate pellets with experimental design equipment. Different manufacturing conditions as the diameter (8 mm − 10 mm), compression force (300 kgf − 500 kgf) and temperature applied during densification (90 °C − 105 °C), were employed in order to evaluate its effect on unit density, bulk density and durability of pellets produced. Values between 0.856 kg/dm^3 and 1.093 kg/dm^3 for unit density, 480.0 kg/m^3 and 603.0 kg/m^3 for bulk density were determined. For durability, values between 96.1% and 97.5% were determined. Significant increase in values determined for unit and bulk density were founded, with diameter reduction and compressive force increasing. Durability was the least sensitive property to the effect of studied densification conditions, whose variation was not significant between similar densification treatments. The effect of temperature generally had less impact on physical properties evaluated. The comparison of results against European standards for wood pellet quality, showed that fabricated pellets fulfills values defined for physical properties in different categories.*

Keywords: *Pellets, densification, unit density, bulk density, durability.*

I. INTRODUCTION

The accelerated population increasing and the necessity of energy for different human activities have caused that the global energy consumption in primary sources has also grown. Data indicates in 2012 the energy consumed worldwide, had the fossil fuels as a source by 80% to 85%[1].

The awareness of low environmental impact of renewable energy sources and high prices of fossil fuels, suggest an increase of renewable energy demand. An example of this type of energy corresponds to energy obtained from biomass, which is a cleaner energy source, and its use implies a reduction of dependence on fossil fuels. Furthermore, its use as an energy source produces CO2 emissions that don’t alter atmospheric carbon concentration, thereby contributing actively to reduce greenhouse gases emissions. Added to this, the management and sustainable energy use of biomass, is closely associated to socio-economic development in rural zones and nations in general, this, because it helps to increase the production of alternative renewable energy; whereby a proper characterization of biomass, it’s vital to know the energy potential available in each region [2].

However, biomass for its intrinsic characteristics has a low energy density, so if it’s desired to get a greater energy potential ratio from this, and improve efficiency in energy obtaining, it’s necessary to increase its density; thereby increasing the amount of calorific energy per unit volume. This type of process is commonly carried out mechanically (with special compaction machinery), and pellets are an example of obtained product by these densification techniques [3].

In relation to pellets and its fabrication, several studies indicate densification of biomass to produce pellets not only corresponds to an increase of energy contain in volumetric terms, it also means a contribution to common problems in solid waste management. In addition, pellet manufacturing means a reduction in transport costs of biomass material, and provides better handling and storage characteristics to this densified biofuel, therefore pellets can be considered as an option to counteract the waste excess, usually generated in agricultural and forestry activities[4].

Moreover, economic and energy sustainability achieved in densification of biomass (largely due to high degree of technological development achieved), has allowed in developed countries in Europe and North America mainly, bioenergy raw materials such as pellets and briquettes made from forest residues, are currently traded internationally, a trend not very common for renewable energy sources, therefore, have been generated quality standards for this type of densified in different European nations [2].

The objective of this study is to determine the physical properties of pellets produced under controlled experimental conditions, also, is evaluated the effect of these densification conditions on determined properties; finally, is established a comparison of results obtained, against the values set to physical properties in main European quality standards.

II. MATERIALS AND METHODS

2.1. Sawmill residues

The pellets were produced from sawmill waste produced in wood processing of Pylon (Hyeronimaalchorneoides) and Eucalyptus (Eucalyptus spp) species. The residual material was collected in combination of sawdust particles and wood shavings (moisture content 35% w.b.). The material was milled using a hammer mill and sifted with a sieve # 10 (2 mm opening). Finally, the material was dried at 60 °C until reaching moisture content of 8% w.b.

2.2. Equipment

Equipment operated by a cylinder-piston system was used to fabricate the pellets (Figure 1). Two cylinders were employed to prepare pellets, these have a length of 15 cm and circular perforations of 8 mm and 10 mm in its longitudinal axis (diameter that will have the pellets). A piston of the same diameter of circular perforations and 25 cm of length, is inserted into the cylindrical cavity to compresses the residue. The equipment was installed in a hydraulic press which plunger applies the force to the piston, and this to the biomass. At the base of the pelleting unit was placed a load cell connected to a digital console, which measures the force applied, this can show readings to 50 000 ± 7 kgf (490.5 kN ± 0.07 kN). In the cylinders were installed a clamp-on electric heater, and a thermocouple directly introduced into the cylinder, allowing to record the temperature with a digital console, which regulates the temperature applied for the heater, keeping constant the temperature in the cylinder. The clamp/thermocouple console has a precision of ±1 °C.

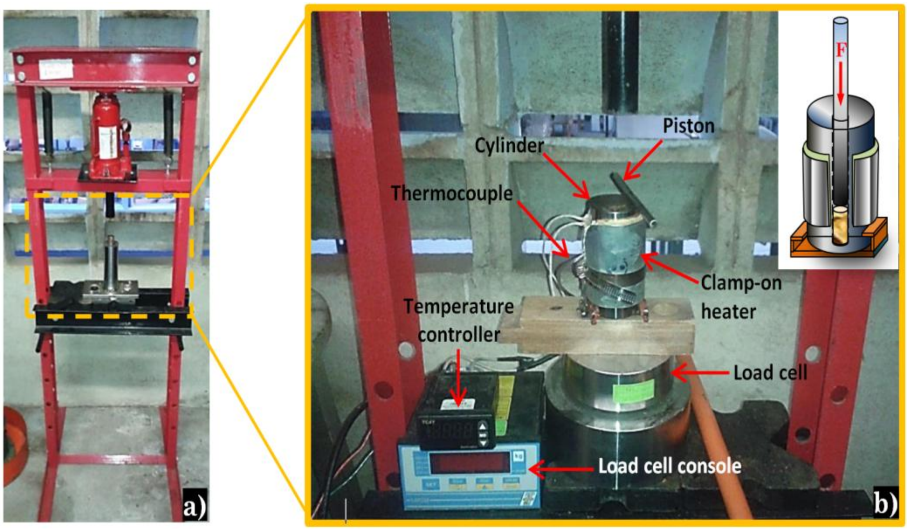

Fig. 1. Experimental equipment used to prepare the pellets
a) Hydraulic press b) Cylinder − piston (and accessories)

2.3. Experimental design

To fabricate the pellets of 8 mm diameter 1.2 ± 0.1 g of residue was deposited on the cylindrical cavity, for the pellets of 10 mm, 2,0 ± 0.1 g was deposited, this in order to obtain similar pellet length (about 2 cm). In the manufacture of pellets was followed a factorial design for treatments applied during the densification; were used two compressive forces 300 kgf (2943 N) and 500 kgf (4905 N), two temperatures (90 °C and 105 °C), and two diameters (8 mm to 10 mm). To form each pellet, biomass was compressed for 60 seconds. In total, eight different combinations of treatments were obtained, as summarized below.

1	x	1	x	2	x	2	x	1	x	2	=	8
Moisture Content		Particle Size		Temperatures		Forces		Time		Diameter		Different Combinations
8% (w.b.)		≤ 2 mm		90 °C and 105 °C		300 kgf; 500 kgf		60 s		8 mm y 10 mm		

2.4. Methodology used in physical properties determination

2.4.1. Unit density

To determinate the unit density (ρ_u), the mass of pellet were measured with a digital balance (precision ±0.01 g), then the diameter and length was measured, so its volume was calculated. Lengths and diameter measuring was performed using a digital caliper (precision ± 0.01 mm). Nine repetitions of this procedure were performed for each of the eight treatment combination studied. The Figure 2 shows the equipment and procedure followed. Unit density was determined using the equation 1.

$$\rho_u = \frac{m_p}{v_p} \quad (1)$$

Where

$\rho_u$unit density (g/dm^3)

$m_p$pellet mass (g)

$v_p$pellet volume (dm^3)

Fig 2 Equipment and procedure followed to determine unit density.

2.4.2. Bulk density

Bulk density (ρ_a) was determined using a cylindrical recipient with a height of 9.0 cm and 7.5 cm in diameter (Figure 3). The methodology followed was based in the Norm ASAE-124 for determination of physical properties of pellets and briquettes. The sample was deposited into cylinder to fill flush with height level, then mass of sample was measured using a digital balance (precision ± 0.1 g). Three repetition of this procedure were performed for eight treatment combination studied, and average was reported. To determine bulk density equation 2 was used.

$$\rho_a = \frac{m_T}{v_c} \qquad (2)$$

Where

$\rho_a$bulk density (kg/m3)

$m_T$total sample mass (kg)

$v_c$cylinder volume (m3)

Fig.3. Equipment and procedure followed to determine bulk density.

2.4.3. Durability

To determine durability of pellets (DU) a cylindrical rotating drum was used. The drum was equipped with two opposite inner baffles placed perpendicular to the cylinder wall. The design of this device and methodology used was adapted from equipment presented by [5] who based on standards CEN/TS and ASAE to determine the durability of pellets. Figure 4 shows the equipment.

The method followed consist in measure the mas of 35 pellets and deposit it in the drum, then the sample was tumbled at 40 rpm to reach 625 revolutions Next, the sample was screened with 2 mm sieve, and finally the mass remaining on the sieve was recorded. Three repetitions of this procedure were performed for each of eight treatment combination studied, and average was reported. Durability was reported as the percentage obtained by the difference between the initial mass of the 35 pellets, and the mass remaining on the sieve after sifting, this percentage was determined using Equation 3.

$$DU = 100 - \left(\frac{m_i - m_f}{m_i}\right) \qquad (3)$$

Where

DU durability (%)

m_i initial mass of 35 pellets (g)

m_f mass remaining on sieve after sifting (g)

Fig.4. Equipment and procedure followed to determine durability.

2.5. Statistical analysis

It was verified the values determined for each treatment combination studied were adjusted to a normal statistical distribution, using a Shapiro-Wilk test using p-values of 0.05 to assume the normality of data from each treatment combination. ANOVA was performed using SNK test, setting p-values of 0.05 to determine significant difference between means of each treatment combination.

2.6. Pellet quality standards

Pellet quality standards, developed mainly in European countries such as Germany (DIN Standards), Sweden (Standards SS) and Austria (Standards ÖNORM), and the normative developed by the European Committee for Standardization (CEN/TS 14961), generally are intended to ensure uniformity of densified biomass and reduce market barriers, to create product flow between producers and users regardless countries or regions [6]. Table 1 show the categories defined in main pellet quality standards in Europe.

Table 1. Parameter established in main pellet quality standards in Europe

Parameter	**Europe CEN/TS 14588**	**Austria (ÖNORM M73135)**	**Germany (DIN 51731)**	**Sweden (SS 187120)**
Size	Ø: 6 mm − 25 mm; $L \leq 5Ø - 4Ø$	Ø: 4mm − 10mm; $L < 5Ø$	Ø: 4mm − 10mm; $L < 5Ø$	Ø< 25 mm; $L < 4Ø - 5Ø$
Moist. content	≤ 10% ; ≤20%	< 10%	< 12%	< 10%
Density	Bulk: to be stated [kg/m^3]	Unit: 1,1 [kg/dm^3]	Unit: 1,2 [kg/dm^3]	Bulk: >500 kg/m^3
Durability	DU≥ 97,5%; DU≥95,0%; DU≥ 90%	≥97,7%	——	> 98,5 %
Heating value	to be stated [kcal/kg]	> 4 302 kcal/kg	3 705 − 4 661 kcal/kg	> 3 609 kcal/kg
Ash content	≤ 0,7% ; ≤ 1,5% ; ≤ 3,0% ; ≥ 6,0%	≤0,5%	< 1,5%	< 1,5%
Nitrogen	≤ 0,3%; ≤ 0,5%; ≤ 1,0%; ≤ 3,0%; >3,0%	< 0,3%	< 0,3%	——
Sulfur	≤ 0,05%; ≤ 0,08%; ≤ 0,1%; >0,2%	< 0,04%	< 0,08%	< 0,08%
Chlorine	≤ 0,03% ; ≤ 0,07% ; ≤ 0,1%; >0,1%	≤0,02	≤0,03%	< 0,03%
Additives	to be stated [%]	< 2 %	——	——

Source: Adapted from [7].

III. RESULTS Y DISCUSSION

3.1. Unit density

Figure 5 shows the variation observed for unit density of the pellets in each treatment. Can be seen for the strength and temperature combination with maximum (500 kgf - 105 ° C) and minimum (300 kgf - 90 ° C) values, unit density has its maximum and minimum values respectively. Also, it should be noted that regardless of the combination force-temperature applied, unit density determined in all cases was higher for pellets fabricated of 8 mm diameter than 10 mm.

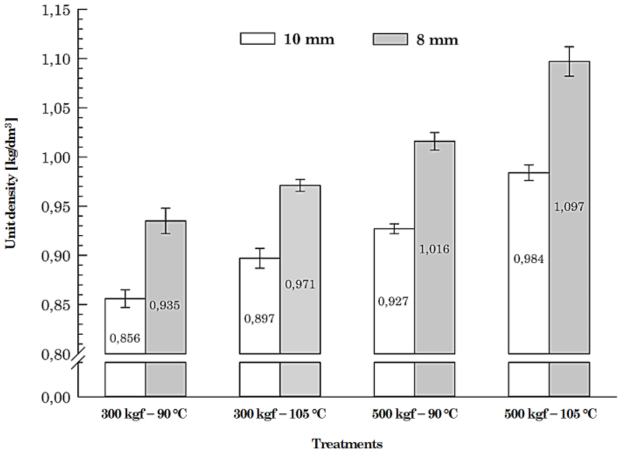

Fig. 5. Unit density of pellets determined for each treatment combination.

This is justified by the effect on the density of each pellet; due to circular area of the cylinder where the biomass is compressed. In a numerically point of view, this is related to the quotient composed of force divided by area (P = F/A) whose product corresponds to the pressure applied to biomass to form the pellet, showing that the pressure applied is inversely proportional to diameter. Therefore, for minor diameter the applied pressure was higher, which consequently means to confine in a smaller volume the same amount of biomass, which ultimately manifested as an increase in unit density. Moreover, compaction pressure (P = F/A) has the scenario of variation due to change force applied for constant pellet diameter, in this case, relation becomes directly proportional, indicating that force increasing is manifested as higher compaction pressure, and vice versa if the force is decreased.

To confirm previously behavior, can be compared in Figure 5, the treatments (300 kgf − 90 ºC) vs. (500 kgf − 90 ºC), or the case (300 kgf − 105 ºC) vs. (500 kgf − 105 ºC). Note in both comparisons that the temperature applied is the same, however, as might be expected, the value observed in unit density increases with force to both evaluated diameters. Rhén et al. [8] and[9] reported the same effect on unit density due to variation of pressure and compression diameter. Another determined effect corresponds to temperature increase in densification process (90 ºC to 105 ºC), where in both diameters, unit density increases if temperature of compression cylinder is increased; this was observed in both cases of compression force (300 kgf and 500 kgf) and for both diameters.Mani[10] and Shankar[11] argued similar conclusions, where the increase of temperature on densification process is closely associated with increments in bulk density.

In Table 2 the results of means comparison for each treatment combination is shown. Significant difference ($p<0.05$) between the mean of six of eight treatments studied were found. Furthermore, it was determined no significant differences between the mean of ρ_u for same diameter independently of treatment temperature−force applied. The only case that presents statistical similarity corresponds to the means of ρ_u for treatments (8 mm – 300 kgf – 90 ºC) and (10 mm – 500 kgf – 90 ºC), however this similarity is due more to the trend data, because analysis of variance between treatments (Diameter×Force×Temperature) showed a significant interaction between treatments ($p<0.05$), indicating the variation of any of treatments, either force, temperature and even diameter, will influence significantly the values determined in ρ_u.

Based on previous analysis, can be established absolute differences for ρ_u in Figure 5. Hence considering the ranges of force, temperature and the diameters studied in this research, can be determined the effect of variation on unit density, manifests most significantly in first instance with diameter variable, in second instance with force variable, and the third case of significance corresponds to temperature variable. Results presented by[9]–[12] suggest similar findings.

Table 2. Results obtained in unit density (ρ_u) determination and means comparison.

Treatment				**Unit Density**	
Diameter (mm)	**Force (kgf)**	**Temperature (ºC)**		**ρ_u(kg/m^3)***	**□ (kg/m^3)**
8	300	90		0.935^a	0.013
		105		0.971^b	0.006
	500	90		1.016^c	0.009
		105		1.097^d	0.015
10	300	90		0.856^e	0.009
		105		0.897^f	0.010
	500	90		0.927^a	0.005
		105		0.984^g	0.008

* $\rho_u$with same superscript are not significantly different ($p<0.05$)

σ: Standard deviation

Another approach of analysis is based on comparison of results against the minimum values to fulfill with European pellet quality standards. Related to this, must be indicated that lower limit value defined as acceptable for unit density, corresponds to 1.1 kg/dm^3; this, if taken as reference standards groups such as described in Table 1. Accordingly, it is possible to determine only the case of pellets of 8 mm diameter and more specifically, pellets made at treatment (8 mm − 500 kgf − 105 ºC) with $\rho_u \approx 1.1$ kg/dm3, have a value according with minimum required.

3.2. Bulk density

Results determined in bulk density (ρ_b) for each treatment combination studied are shown in Figure 6. It is observed that, like the unit density, bulk density shows a behavior tended to increase under the force and temperature are maximum within ranges tested (500 kgf − 105 °C), accordingly, the lowest values in bulk density were observed for treatment combination with lower force and temperature values (300 kgf − 90 °C). Another similar behavior to unit density, correspond to the bulk density of pellets made of 8 mm diameter is higher than 10 mm pellets, this regardless the treatment combination analyzed. Meanwhile, it is also confirmed that any increase in temperature or force, introduced a tendency to increase bulk density, this was also observed if the diameter is decreased; These three cases were observed equivalently for unit density, so can be observed the close relation between unit and bulk density. This relation between densities was exposed similarly by[8], [11]–[13].

Table 3 shows the results of means comparison for (ρ_b) in each treatment combination. Significant difference (p<0.05) was found between means for all combinations studied, confirming any variation in diameter, force or temperature will incur in a significant change on bulk density, compared to any other combination, hence, again densification conditions as the diameter, compressive force and temperature applied have preponderance on pellet properties, in the same way as confirmed for unit density. Similarly, [13] and [14] observed tendency to rise bulk density if temperature and compression force is enhanced, as shown in Figure 6.

Based on previous analysis, can be established from Figure 6 that bulk density is modified significantly, in greater proportion with variations in the compressive force; second case of significance if diameter is modified, and with less effect was found temperature variation. Note that in this case, the order of significance differs from obtained for unit density, where the greatest effect on ρ_u was determined due to diameter modification.

Table 3. Results obtained in bulk density (ρ_b) determination and means comparison.

Treatment				**Bulk density**	
Diameter (mm)	**Force (kgf)**	**Temperature (ºC)**		**ρ_b(kg/m^3)***	**σ(kg/m^3)**
8	300	90		505.6 ^{a}	1.1
		105		530.3 ^{b}	1.0
	500	90		577.1 ^{c}	1.1
		105		603.0 ^{d}	1.2
10	300	90		480.0 ^{e}	1.2
		105		496.8 ^{f}	1.1
	500	90		534.2 ^{g}	1.4
		105		552.3 ^{h}	1.5

* $\rho_b$with same superscript are not significantly different (p<0.05)

σ: Standard deviation

Regarding the comparison of data against values established in pellet quality standards, should be noted that bulk density is a physical property mainly related to pellets storage and transportation operations; However, beyond being a physical property, it is also closely related with slower combustion behaviors and higher energy content per volumetric unit [12], [15].

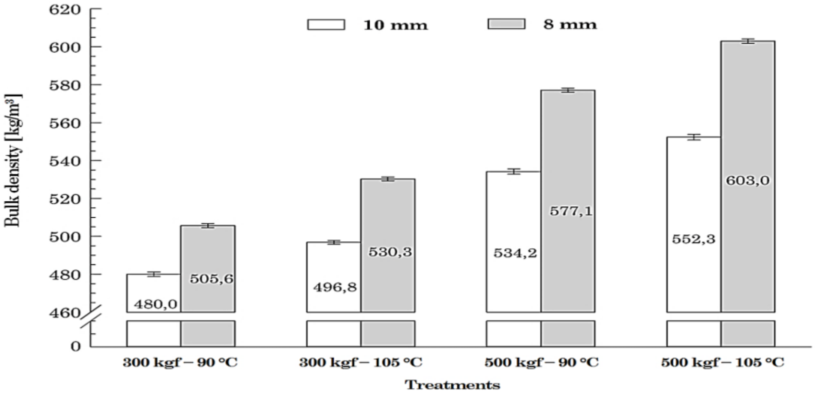

Fig.6. Bulk density of pellets determined for each treatment combination.

Although the value of bulk density does not appear as an explicit value in all standards summarized in Table 1, it is necessary to state the value. Taking a reference the case of Swedish standard (SS187120), bulk densities equal or exceed 500 kg/m^3 are normally acceptable. Accordingly, it is evident in Figure 6 and Table 3 that six of eight treatments applied to fabricate the pellets, result in bulk densities higher than 500 kg/m^3, except for treatments corresponding to (10 mm − 300 kgf − 90 °C) and (10 mm − 300 kgf − 105 °C) with bulk densities of 480.0 kg/m^3 and 496.8 kg/m^3 respectively. Moreover, it emphasizes that for all treatment combinations, pellets made of 8 mm diameter fulfill satisfactorily the value commonly established for ρ_b.

3.3. Durability

Figure 7 shows the variation observed in durability of pellets (DU) for each treatment combination. It is evident DU behaves equivalent as has been the trend in results for unit and bulk density; since DU tends to improve (increase) with the increase in compressive force and temperature. Furthermore it is noted the values for DU always are higher when pellets are prepared to 8 mm diameter, over fabricated of 10 mm, if the same treatment force−temperature is compared.

As observed in unit and bulk density, variables modified in densification acquire special importance on values determined for DU, from this, the tendency of DU to be varied even if one of treatments is modified. This also showsthe quite narrow relation between DU, bulk and unit densities; since the factors that introduces unit and bulk densities increase also will incur in hardness increases [9]. In relation with this, [12] expose that the combined effect of pellet diameter decreasing added to the increase in temperature, manifested in a higher activation of gelatinization properties of biomass, which improves the hardness of pellets. Similarly, [16] point out increasing the compression force and temperature applied during densification trend to develop solid bridges, due to molecules diffusion between biomass particles, creating contact points that are manifested at macroscopic level as increases in pellets density and hardness. Complementarily, [17] suggest the moisture present in biomass acts like a binder and causes Van der Waals forces between particles, this will eventually improve density and durability.

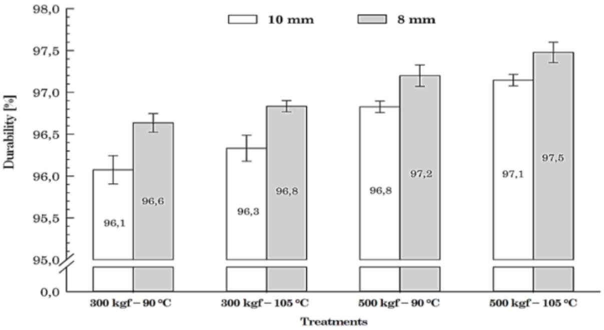

Fig.7. Durability of pellets determined for each treatment combination.

Is shown in Table 4, as from means comparison, no significant differences for DU were determined in treatments (10 mm − 500 kgf − 90 °C), (8 mm − 300 kgf − 90 °C) and (8 mm − 300 kgf − 105 °C), which means in terms referring to DU to applying either of these three treatments, will result in a similar hardness. Besides, it is important refer to the effect of these three treatments on DU, in terms of densification process, because is possible to note that in in two of the cases, if 8 mm diameter and force of 300 kgf are maintained, an increase in temperature did not mean a significant increase in DU, although during densification process more energy investment was required to increase the temperature of pelleting unit. In the case of treatment (10 mm − 500 kgf − 90 °C) was necessary to increase the compression force regard to the other two significantly similar treatments, which only required change to a smaller diameter to achieve a similar DU, confirming the effect of increasing DU introduced by modify the pellet diameter.

Table 4 Results obtained durability (DU) determination and means comparison.

Treatment				**Durability**	
Diameter (mm)	**Force (kgf)**	**Temperature (ºC)**		***DU* (%)***	***σ*(%)**
8	300	90		96.6 ^{a}	0.1
		105		96.8 ^{a}	0.1
	500	90		97.2 ^{b}	0.1
		105		97.5 ^{c}	0.1
10	300	90		96.1 ^{d}	0.2
		105		96.3 ^{e}	0.2
	500	90		96.8 ^{a}	0.1
		105		97.1 ^{b}	0.1

* *DU* with same superscript are not significantly different (p<0.05)
σ: Standard deviation

Another not significant difference is observed for the means of DU for treatments (10 mm − 500 kgf − 105 °C) and (8 mm − 500 kgf − 90 °C) with DU=97.1% and DU=97.2% respectively. Note for the first of these two cases, the greater force and temperature were applied, however DU determined is not significantly different from pellets manufactured of (8 mm − 500 kgf − 90 °C); while it is true was applied the same compression force (maximum), it was not necessary to apply greater temperature in densification to achieve similar DU; so again the effect due to diameter decrease on DU is observed.

Moreover, in Table 4, DU does not varies significantly for all treatments; on the contrary, means of five treatments can be grouped (indicated with same superscript), a situation not observed in the analysis of unit and bulk densities, where for all treatment combinations significant differences was observed. According to this, is determined that durability is the less sensitive of the studied physical properties to changes in treatments ranges evaluated. Results reported by [9] and [18] showed the same trend under different pelleting conditions. Meanwhile, [16] presented results with same tendency for different biomasses.

Finally, if DU results are compared against values defined in the standards summarized in Table 1, can be established for treatments here applied, that only densification under treatment (8 mm − 500 kgf − 105 ° C) results in a durability of97.5%, thus fulfilling with values defined for DU in CEN/TS 14588 standard, and not for the others reviewed standards. Nevertheless, it is worth noting that CEN/TS 14588 standard have categories that accepts values for DU ≥ 95.0 % and even DU ≥ 90.0 %, so all treatments applied result in high DU enough to comply the value established for this parameter, since for example the lower determined durability was 96.1 %.

In relation to DU, [9] emphasize that DU values above 90% can be considered with an acceptable durability. Theerarattannoon et al.[18]indicate that pellets with durability above 80% even can be considered as "highly resistant". Furthermore, [19] report that pellets with high DU are preferred because problems mainly detected in the storage, transportation and combustion chambers, normally are associated to pellets with low DU disintegrate easily.

IV. CONCLUSIONS

Successful manufacture of pellets from sawmill residues was achieved for all treatments and combinations studied. It was generally observed better physical properties when minor diameter of densification, higher compressive force and temperature was set in the pelleting unit. Unit density is influenced more significantly by diameter variable. Meanwhile, significant variation in bulk density was observed, mainly due to the effect of compression force. The effect of variation on physical properties due to the pelleting temperature is the slightest determined. Durability is the less sensitive property to variation of densification treatmentsevaluated. Generally, it was concluded the sawmill residue used, the diameters selected, and compressive force and temperature applied, results in pellets with physical properties that fulfills in fairly way with values specified in the most demanding European pellet quality standards.

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