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## Original Article

# Assessment of iron ore pellets production using two charcoals with different content of materials volatile replacing partially anthracite fines



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## ABSTRACT

Iron ore pelletizing plant consumes coal, pet coke, oil and natural gas to get the required chemistry, physical and metallurgical properties for iron ore pellets, consumed in steel industry. Tests were carried out to burn green iron ore pellets, which consumed natural gas; coal (anthracite fines) and two different eucalyptus charcoal (replacing the anthracite fines partially) with two different range of volatile materials. First charcoal with a volatile range of 20.3–25.98% and, a second one varying from 9.4 to 11.1%. Based on fixed carbon (10 kg/1 ton of pellets) content in green mixture, several tests were done to replace approximately 0.0, 7.5, 10.0 and 35.0% of anthracite fines by the two different charcoals, each turn with one charcoal, at the end both charcoals were tested and replaced the anthracite fines in the same amount of fixed carbon content. The “zero” replacement was the standard pellet trial, produced only with anthracite fines. Experiments were performed on a pilot scale plant using a mixer for green mixture, pelletizing disk, and a reactor of “pot grate” type for burning green pellets, that reactor simulated the traveling grate indurating machine. After burning, samples were collected to undergo physical tests, such as: tumble, abrasion and crushing strength. It was possible to replace 7.5% of anthracite fines by the two eucalyptus charcoal. Still 10.0% of replacement of anthracite fines was possible with the charcoal with lower volatile matter.

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## 1. Introduction

The steel industry has negative implications in terms of pollutant emissions. The energy consumption of that industry is approximately 24 EJ/year, which represents 5% of the planet's primary energy consumption and corresponds to approximately 3–4% of global CO<sub>2</sub> emissions [1]. This is an important reason to study the replacement of fossil fuels in that industry, and result in less pollution. An excellent substitution to the fossil fuel can be eucalyptus charcoal which is a source of biomass.

Currently, coal is one of the main inputs of pelletizing iron ore. Wendling [2] showed that the addition of coal in pellets began in the 1990s, with the Gulf War and the oil crisis, and found several advantages for the usage of coal in the iron ore pelletizing process.

The reactivity of different mineral coals and pyrolyzed carbons depends on several factors, in particular [3]: the porosity of the coal, that is, its internal structure, surface and active sites, the crystalline structure of the fixed carbon, and the catalytic effects of ash components on coal.

Pyrolysis is a process of thermochemical decomposition of biomass in compounds that depend on the composition of the lignocellulose carbohydrates of each type of biomass. Thus the product of decomposition is a function of the biomasses individually [4].

Biomass pyrolysis typically occurs in the range of 400–700 °C. Below combustion, which occurs between 800 and 950 °C [5].

Carvalho [6], in a conceptual study on the technical and economic viability of the synthesis gas for the pelletizing of iron ore in an indurating traveling grate, investigated the usage of gasification in iron ore pelletizing process. Gasification equipment was studied for a pelletizing plant with annual production capacity of 8.4 million tons of pellets/year and thermal consumption of 206.1 kcal/kg of pellet. The objective of that study was preliminarily to evaluate the partial replacement of the natural gas injected into an indurating pelletizing machine by synthesis gas from gasification of eucalyptus chips.

The reason of this study is to evaluate the partial replacement of anthracite coal used in Brazilian iron ore pelletizing industry by eucalyptus charcoal. In Brazil iron ore pelletizing is an important economic activity, with a large volume of production and relevant thermal consumption (remarkably coal, heavy oil and gas), development of alternative fuels, such as eucalyptus charcoal, can generate relevant environmental, economic, technological and social benefits.

This research relied on all those past knowledge to head a new approach, not yet utilized neither tested in pelletizing of iron ore, which is the usage of eucalyptus charcoal in its process. The consumption of coal is consolidated, although that is a recent (1990s) activity; but the usage of coal together with eucalyptus charcoal is practically unknown. Studies on the application of eucalyptus charcoal in iron ore sintering are already more frequent. A study reference for this work, because it holds many similarities is the study of Tôrres et al. [7], in that study anthracite fines coal was replaced by a biomass of leather tannery waste.

Tôrres et al. [7] performed experiments similar to that proposed in this study. For that study a biomass charcoal was produced from carbonized leather residues (CLR) waste. That waste undergoes a pyrolysis process resulting in a biomass charcoal, which was tested in the same pilot plant pot grate of iron ore pelletizing of this study. That waste was dosed with satisfactory results, with good replacement of anthracite fines, ranging dosage from 10% to 25%. The crushing strength of the pellets was values of 344 kgf/pellet, at a dosage of 25%, compared to the result of the standard pellet with 100% mineral anthracite fines, which was 300 kgf/pellet, a good result, since it was possible to overcome the standard.

The results of this study are connected to the combustion and thermal decomposition behaviors of solid fuels inside iron ore pellets. So it is a key knowledge comprehends the pellet hardening process, it means mainly understands fuel solid combustion inside pellets, because inappropriate combustion can spoil pellet qualities properties.

### 1.1. Summary – indurating machine

This is a summary of the indurating traveling grate machine of the study sponsor. Pellet hardening takes place on the traveling grate, which is part of the indurating machine. The traveling grate is covered by a refractory lined hood, which is divided into the following process zones (inside round brackets are an usual range of gas temperature admitted for processing hematite ore – [8]): A – Updraft drying zone (UDZ) with process gas from second cooling (350–400 °C); B – Down draft drying zone (DDZ) with process gas from the windbox recuperation system from firing (D) and after firing zone (E) (350–400 °C); C – Preheating with recuperated hot process gas from first cooling (1000–1050 °C); D – Firing with oil/natural gas burners and using recuperated hot process gas from first cooling (1000–1050 °C); E – After firing with hot process gas from first cooling (1000–1050 °C); F – Cooling I and Cooling 2 admit atmospheric gas at local temperature to cooling the pellets. This temperature profile is shown in Fig. 1.

Important to note that there is no thermocouple to evaluate the pellet layer temperature and this is a tough issue because the pallet car is like a refractory metal container in motion (like a train wagon), connected in a sequence of hundreds pallet cars and it is impossible, so far, install thermocouples for that temperature control. That is the reason because just process gas temperature is followed up. It is remarkable to note that process gas temperatures are not the same of the material layer. Despite that be a simple consideration it is important remember that, whereby, there is going to be impacts in this tests.

## 2. Materials and methods

Two samples of eucalyptus charcoal were acquired from local producers, and their origin come from pyrolysis of eucalyptus trees. That pyrolysis, just for the purposes of this study, is called first pyrolysis. Half of each eucalyptus charcoal sample was undergone to a second pyrolysis in this study. Finally, eucalyptus samples were set to grinding.

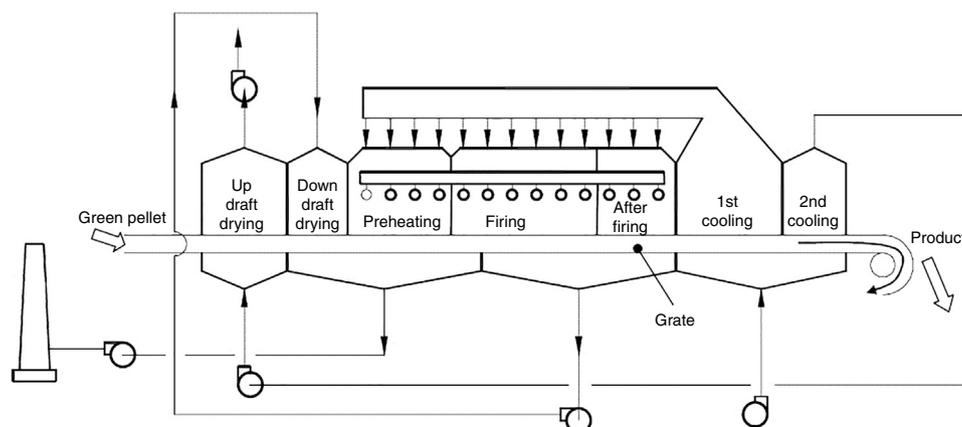


Fig. 1 – Thermal profile of pelletizing indurating machine.

Pellet feed, bentonite, limestone, and anthracite fines, also were collected and their origin came from the mining company sponsor of this study. Those materials were applied to the experiments as collected. The anthracite fines were subject to drying and grinding prior to the green mixture. After fuel grinding, all raw materials were set for mixing (green mixture production), pelletizing (balling) and at last burning tests of green pellets in a scale pot grate furnace.

Each green mixture was matter of mass balance. At first, the raw materials were chemically analyzed, with the results obtained, mass balances were performed, and then the dosages of each compound were established for each one of the seven tests. Subsequently, mixing of green mixture, pelletizing and burning of the green pellets were performed. The burned pellets samples were chemically analyzed and subjected to physical tests [9,10].

Two samples of anthracite fines were collected and prepared. Those were identified as AF1, and later when the AF1 sample was consumed in green mixtures experiments from 1 to 5, a new sample of anthracite fines was provided for green mixtures experiments 6 and 7, that new sample was renamed AF2.

Eucalyptus charcoal 1, was called CHAR 1 and was used in experiments 2 and 4. The other half of CHAR 1 which was underwent to the new pyrolysis, after that, was renamed CHARPY 1. CHARPY 1 was consumed in experiments 3 and 5. After the consumption of all sample of eucalyptus charcoal 1, it was necessary a second eucalyptus charcoal sample, renamed as CHAR 2. Half of CHAR 2 was utilized in experiment 6 and, and another half was pyrolysed and became CHARPY 2. CHARPY 2 was consumed in experiment 7.

A summary of the fuel mixture composition applied for each green mixture is presented in Table 1, in terms of fixed carbon content contribution. Fixed carbon need to be 1% in mass of green pellets (10 kg fixed carbon/1 ton of pellets).

### 2.1. Fuel preparation

AF1, AF2, CHAR1, CHAR2, CHARPY1 and CHARPY2, were all ground in pilot ball tube mill. The grinding of the CHAR (1 and 2) and the CHARPY (1 and 2) took 15 min; the grinding of the AF took approximately 30 min. After grinding, the fuels were

Table 1 – Mixture fuel composition applied for each green mixture.

Test	Mixture fuel composition
1	AF1 – 100.0%
2	AF1 – 92.5% + CHAR1 7.5%
3	AF1 – 92.5% + CHARPY1 7.5%
4	AF1 – 90.0% + CHAR1 10.0%
5	AF1 – 90.0% + CHARPY1 10.0%
6	AF2 – 65.0% + CHAR2 35.0%
7	AF2 – 65.0% + CHARPY2 35.0%

available to be mixed with pellet feed, limestone and bentonite to prepare the green mixture, for balling and at last burning.

The Sponsor of this study, in its operations has as target of specific surface area of at least 5000 cm<sup>2</sup>/g, and 40% passing through the 44 μm sieve for anthracite fines. As there was no experience with eucalyptus charcoal in the operations of the sponsor company, those values were adopted as reference for the grinding of the charcoals. Those parameters are important subject to be evaluated in future studies.

Thermogravimetric (TGA) tests were performed on the six solid fuels used in the burning tests. Thermogravimetric experiments were performed with Navas Instruments 2000 model equipment, with a continuous flow of high purity nitrogen gas at the rate of 50 ml/min.

The volatile test was carried out in accordance with the international standard ISO 562: 2010, Hard Coal and Coke – Determination of Volatile Matter.

### 2.2. Mixtures and pelletizing (balling)

Seven tests (seven different mixtures) were performed with seven different fuel compositions. Each test corresponds to two burnings in pot grate, a first burning (called A) and a second one is a duplicate (called B), to check the variability and repeatability of the process and corrections if necessary. Each test consumed approximately 140.0 kg of pellet feed mixture, limestone, bentonite, anthracite fines and eucalyptus charcoal. The green pellet composition of A and B is the same.

The calculations were made to achieve the following goals: (a) the limestone dosage should lead to 0.85% CaO in the burned pellet; (b) fixed carbon dosage in experiments 1–7



**Table 4 – Immediate analysis, LCV and sulfur content.**

Fuel and test number	Fixed carbon (%)	Volatile (%)	Ash (%)	LCV (cal/g)	S (%)
AF1 (1-5)	72.08	10.17	17.75	6676	0.89
AF2 (6-7)	70.03	12.30	17.67	6564	0.90
Average	71.06	11.24	17.71	6620	0.90
CHAR 1 (2 and 4)	72.81	25.98	1.21	7052	0.03
CHAR 2 (6)	77.88	20.32	1.80	7312	0.03
Average	75.35	23.15	1.51	7182	0.03
CHARPY 1 (3 and 5)	86.93	11.14	1.93	7801	0.03
CHARPY 2 (7)	86.79	9.37	3.84	7721	0.12
Average	86.86	10.26	2.89	7761	0.08

### 3.1. Solid fuel applied in green mixture and balling

The immediate analysis, low calorific value (LCV) and sulfur content of the solid fuels utilized in the tests 1-7 are presented in Table 4.

Pyrolysis of CHAR 1 and CHAR 2 produced CHARPY 1 and CHARPY 2 with a significant reduction of volatile matter. These volatile values found are according to the literature, Garcia [11], Cortez et al. [4] and IPT [12].

The particle size distribution of the six fuels utilized in the 7 green mixtures is shown in Fig. 2.

Fig. 2 shows the particle size distribution of each one of the 6 fuels used in the 7 green mixtures, for pelletizing and burning. Despite of the variation in the grain size distribution, especially in the fractions smaller than 44  $\mu\text{m}$ , all those fuels were within the target applied by the sponsor in its routine operation. It is important to note that in daily operation of the study sponsor, the size control parameter is the average specific surface.

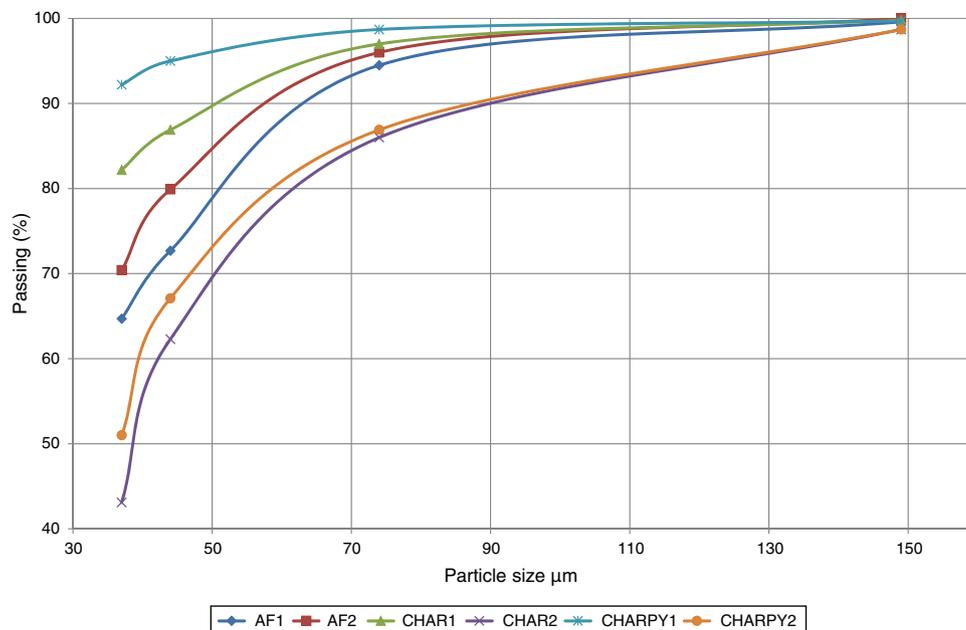
Also in Fig. 2, the values found for the six fuels, CHARPY1, CHAR1, AF2, AF1, CHARPY2, CHAR2 in the order of the smallest to the largest grain size were: 95.0%, 86.9%, 79.9%, 72.7%, 67.1% and 62.3% respectively for passing through 44  $\mu\text{m}$ .

The average specific surface area of the six fuels used in the green pellet mixtures for balling and burning are shown in Table 5.

In a similar research with iron ore in pot grate made by Tôrres et al. [7], however using a charcoal originated from carbonization of leather residues (CLR), the size of CLR was similar to CHARPY1 and CHAR1. Those biomasses and CLR presented the following values for the size of passing through 44  $\mu\text{m}$ : CHAR1, CHARPY1 and CLR were 86.9%, 95.0% and 88.8%, respectively. The CHAR2 and CHARPY2, passing through 44  $\mu\text{m}$  were 62.3% and 67.1%, respectively. The different size distribution presented different impacts on combustion and heat distribution in the green pellets. Passing higher than 86.9% through 44  $\mu\text{m}$  as CHAR1, CHARPY1 and CLR had better combustion and heat transfer inside the pellets.

### 3.2. Solid fuel thermogravimetry and fuel behavior in pot grate

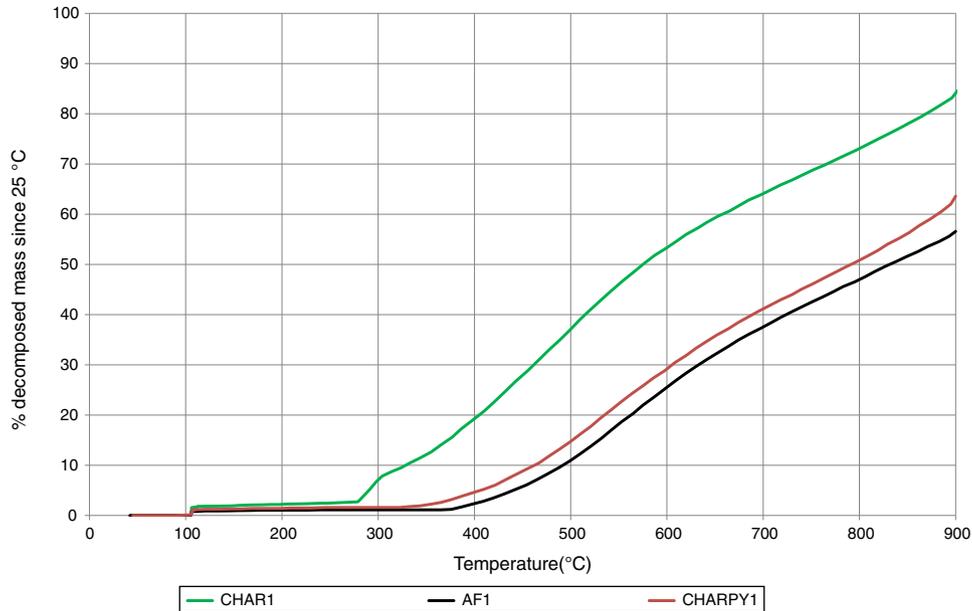
In relation to the thermogravimetric curve, a very distinct behavior between CHAR, AF and CHARPY, used in tests 1-7 were presented. This behavior is depicted in the thermogravimetric graphics. Fig. 3 shows the thermogravimetric graphic



**Fig. 2 – Particle size distribution of the fuels used in the seven green mixtures.**

**Table 5 – Average specific surface area of the solid fuels tested.**

	AF1	AF2	CHAR1	CHAR2	CHARPY1	CHARPY2
(m <sup>2</sup> /g)	12,500	5333	11,765	8511	13,333	9524

**Fig. 3 – Thermogravimetric decomposition, tests 1-5.**

for fuel from tests 1 to 5. It is important remark that the behavior in thermogravimetric curve presents relevant implications in the indurating process and consequently quality parameters of the burned pellets.

Fig. 3 the first fuel to start decomposition at the lowest temperature is CHAR1, after raising temperature, was followed by the CHARPY1 and at last to decompose was the AF1, the initial decomposition temperatures were 279 °C, 355 °C and 365 °C respectively. Both fuels keep approximately the same rate of decomposition and the same delta of temperature ( $\Delta T$ ) for a same mass of decomposition between the three curves until 900 °C. This means that CHAR1 decomposition will always, in this case, happen at first place and the decomposition of CHARPY1 second but very close to AF1. This happens because CHAR 1 has higher volatile matter.

For each fuel applied, the decomposition behavior need to be reasoned inside the green pellets, when the burning process happens. The CHAR1 starts its thermal decomposition in lower temperatures than AF1 and CHARPY1. That factor generated a worse pellet, because that decomposition (CHAR1) was advanced when compared to the others fuels (AF1 and CHARPY1), thereby worsening the hardening process and consequently pellet quality. In this study that issue is considered the hypothesis of thermal decomposition of charcoal and its effects take place inside a green pellet, during the hardening process in the moving grate.

Clearly the usage of fuels with charcoal provided a type of pellet that tends to be dusty, this factor probably due to the results obtained, is linked to the hypothesis of thermal decomposition.

It is not clear exactly which the lower temperature is, more studies need to be done to understand how to define that lower temperature. That lower temperature is related to the types of fuels used. However it is remarkably clear by the thermogravimetric curves that this process happens. On the other hand just viewing the thermogravimetric curves it is possible to assume that if the pellets are in a range of temperature of approximately 300–400 °C, the decomposition starts, pay attention that the surface pellet and inside pellet temperatures are not the same. This is a complex discussion for this study and will not evaluated here, possibly this range is reached somewhere between DDZ and preheating zone. Anyway the result is a dusty pellet in some extension.

In the second thermogravimetric curve, referring to the fuels of tests 6 and 7 in Fig. 4, a behavior similar to that of Fig. 2 was presented, that is, at first CHAR2 begins its decomposition at temperatures below 300 °C, in the case 248 °C. On the other hand AF2 and CHARPY2 decompose at temperatures of 348 and 349 °C, respectively. The CHARPY2 curve presented behavior similar to that of AF2, differently from CHAR2. Thus, CHAR2, like CHAR1, underwent thermal decomposition at lower temperatures.

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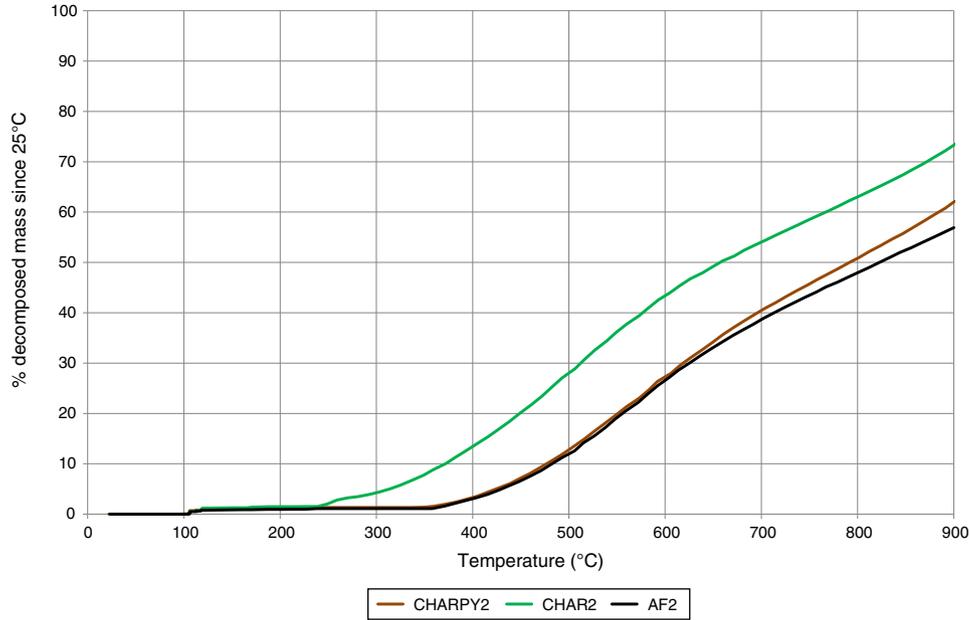


Fig. 4 – Thermo gravimetric decomposition curve of AF2, CHAR2 and CHARPY2, used in tests 6 and 7.

Table 6 – Maximum average temperature reached in during the firing tests.

Average temperature in the pellets			
Upper layer (°C)	Middle layer (°C)	Lower layer (°C)	Windbox (°C)
1381	1373	1355	632

3.3. Physical and chemical properties obtained in burned pellets

During the seven tests there was no significant variation in process temperatures, as shown in Table 6.

There were no significant temperature variations during the 7 tests. The heat distribution according to the temperatures reached was uniform and sufficient for the maximum recrystallization of the hematite to occur around 1350 °C.

Remembering that consumption of natural gas was kept constant. It means that around 50% of the total thermal balance came from natural gas and the other 50% came from solid fuel (one of those: AFs, CHARs and CHARPYs).

An important remark is the thermal monitoring of pellets in pot grate is possible because in lab scale equipment (pot

grate) is a static pot different from the real pallet cars that are in motion during operation.

3.4. Chemical analysis

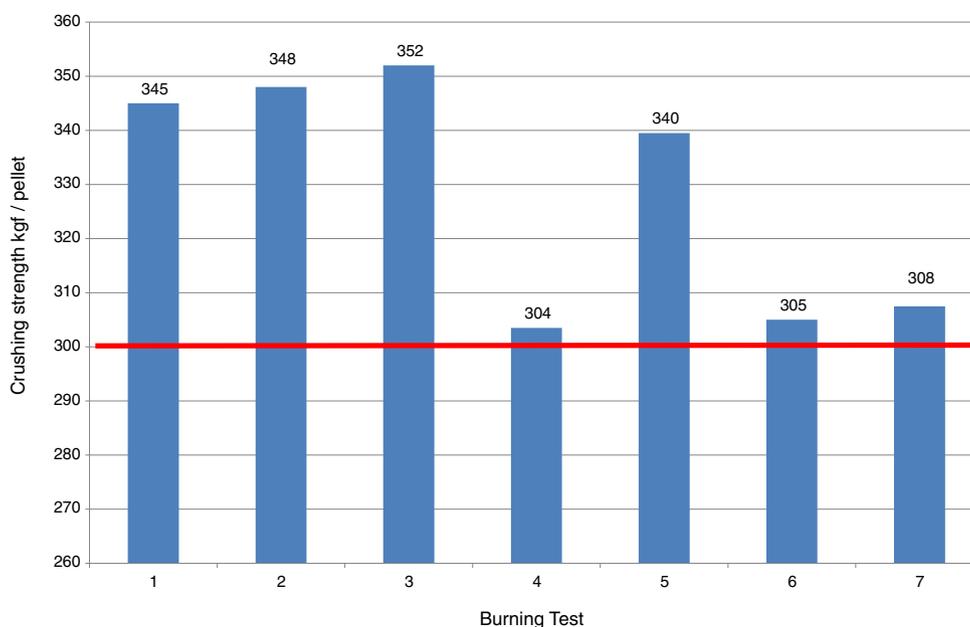
The results of chemical analysis from samples after pellets were burned are presented in Table 7.

3.5. Crushing strength

Fig. 4 shows the average crushing strength in kgf/pellet obtained from samples from the seven burning tests. The red line represents the minimum average crushing strength (300 kgf/pellet) required in the total amount production of pellets from the productive process of the study sponsor.

Table 7 – Chemical analysis from burned pellets for tests 1-7.

Description	1	2	3	4	5	6	7
FeT (%)	66.98	67.22	67.2	67.12	67.23	67.23	67.24
SiO <sub>2</sub> (%)	2.10	2.04	2.08	2.14	2.05	2.01	2.01
Al <sub>2</sub> O <sub>3</sub> (%)	0.56	0.58	0.55	0.56	0.56	0.53	0.53
CaO (%)	0.96	0.89	0.87	0.93	0.88	0.9	0.88
MgO (%)	0.12	0.10	0.12	0.10	0.12	0.11	0.12
P (%)	0.056	0.057	0.056	0.059	0.056	0.056	0.057
Mn (%)	0.06	0.061	0.062	0.059	0.059	0.06	0.059
TiO <sub>2</sub> (%)	0.058	0.059	0.059	0.06	0.061	0.059	0.06
Basicity	0.46	0.44	0.42	0.44	0.43	0.45	0.44



**Fig. 5 – Average crushing strength of burned pellet samples from the seven burning tests.**

Considering only the values presented in Fig. 5 and comparing these with those from literature, it can be seen that the values of crushing strength obtained in the 7 burning tests were similar and even better than those available in literature as Vale [13], LKAB [14], Umadevi et al. [15] and Geerdes et al. [16] with values of at least 250 kgf/pellet, 219 kgf/pellet, 260 kgf/pellet, and 150 kgf/pellet respectively.

The hypothesis of thermal decomposition of charcoal and its effects inside a green pellet that is hardening in the moving grate

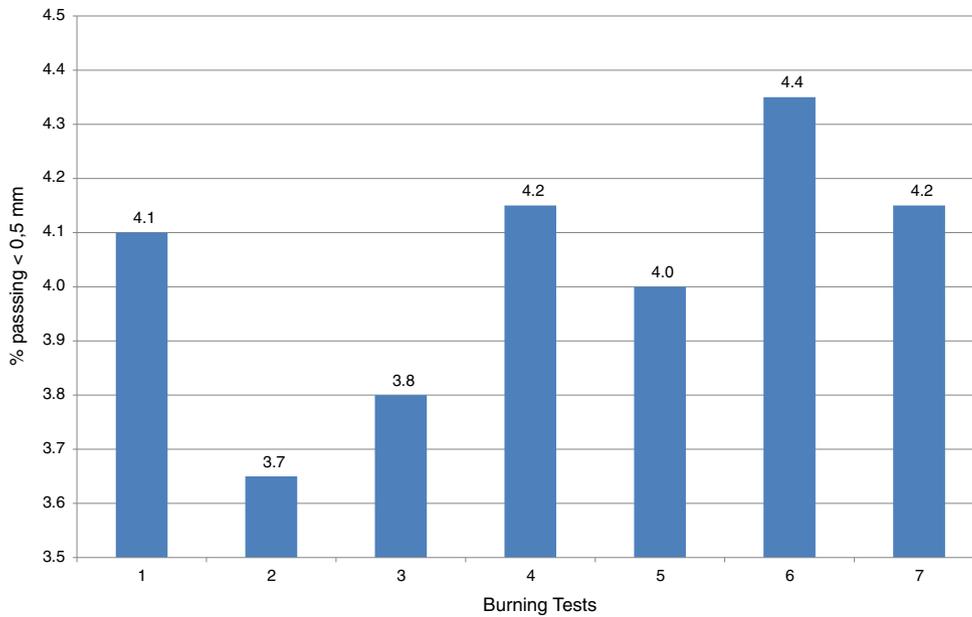
Tests 1 (standard), 2 (CHAR 7.5%), 3 (CHARPY 7.5%) and 5 (CHARPY 10.0%) presented similar results and were the best results of crushing strength. So far, it is possible to accept that some surge of the volatile matter inside the green pellets do not prejudice the consolidation of those until higher temperatures (burning zone temperature). As of certain amount of volatiles those are released in advance (thermal decomposition happens at lower temperatures than should be, when compared to AF) from solid fuels particles creating cracks inside pellets in advance and probably before burning zone, therefore weakening pellets before a final consolidation in the burning zone, there is even the possibility of combustion. This is the hypothesis of thermal decomposition of charcoal. The presence of those cracks weakened pellets and reduced their strength as presented. Those cracks are created because decomposition and combustion happens in advance, but still this process need to be better investigated.

Tests 4 and 6, with the highest amount of CHAR, presented a crushing strength drop of 11.9% and 11.6% respectively in relation to test 1. The resistance drop in those tests were related to the hypothesis of thermal decomposition, it means that CHAR1 in test 4 (10% of carbon content) and CHAR 2 in test 6 (35% of carbon content) had enough volatile matter to start decomposition and combustion earlier. Volatilization

occurred at temperatures below 300°C, with combustion occurring [17], thus, additional internal stresses appeared inside the pellet burned, besides the vaporization of water [2,18]. So the hypothesis of thermal decomposition can be applied for those tests.

In relation to fuel size effect in combustion, passing through 44 µm of CHAR1 and CHAR2 presented 86.9% and 62.3%, respectively. Similar test to this study was the work done by Tôrres et al. [7]. That study had similar requirements of the mass balance of this study, but using the charcoal leather residues (CLR) with particle size in 44 µm, smaller than 88.8%, and therefore obtaining crushing strength results when the dosage included CLR better than the standard of their test. Tôrres et al. [7] mentions the hypothesis that a biomass, with the size of their test, could improve the heat transfer distribution inside the pellets during the burning process. In this test 6, the CHAR2 with the highest size was unfavorable to the hypothesis of a better distribution of energy in the pellet, being this one of the factors that led to the decrease of the crushing strength.

Crushing strength drops in test 7: That drop in resistance is associated with the following factors: (a) When comparing test 7 to tests in the literature such as Tôrres et al. [7], which consumed CLR with 25% of fixed carbon, the variations of crushing strength against their test standards are –12.5% and +14.7%, respectively. The CHARPY2 presented greater granulometry compared to the CLR, passing through 44 µm were 67% and 88.8%, respectively. The CHARPY2 presented higher LCV in relation to CLR, 7721 kcal/kg and 4968 kcal/kg, respectively. So, the study of Tôrres et al. [7] shows that there was a better distribution of thermal load in the CLR pellet when compared to test 7 of this study. (b) All the six previous tests applied 1.0% of fixed carbon content, but this test had the highest amount of fixed carbon per mass of dry mixture 1.062%, or 6.2% more than the others.



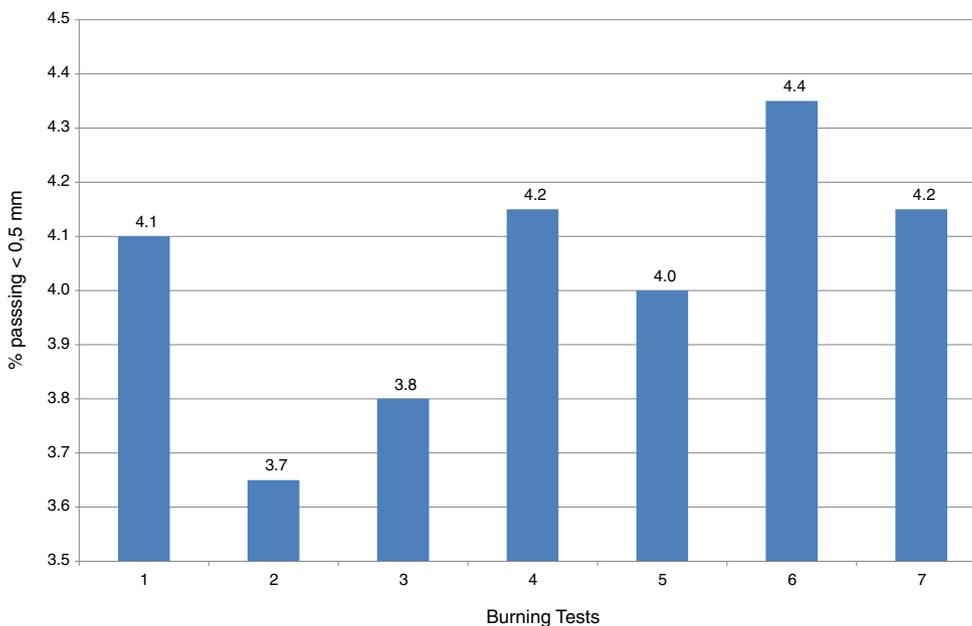
**Fig. 6 – Comparison of the percentages of pellets burned with crushing strength less than 200 kgf of this study with different charcoals and the study with biomass from leather tanning (CLR).**

Testing the percentage of pellets below 200 kgf/pellet is not a standard procedure so it is not standardized by study sponsor or internationally. It is an internal procedure of the sponsor, when conducting its research; it uses this practice of making this measurement in order to better understand the variability of the process.

Fig. 6 shows the percentage of pellets burned in each burning test with crushing strength less than 200 kgf of this study (blue bars) and compares these to the results obtained by Tôres et al. [7] (red bars).

Analyzing Fig. 6, it can be seen that tests 1, 2, 3 and 7 have the best results, with smallest amount of material

below 200 kgf/pellet. The tests 5, 6 presented intermediate values and test 4 had the worst result. The above results agreed with Fig. 5, which, presented that tests 1, 2 and 3 had gotten the best crushing strength. It is also possible to observe that the results of CHARPY samples had been better results than CHAR for a same amount in fixed carbon (for instance, comparing test 4 and 5 because it has the same biomass content, in the case of 10.0% of fixed carbon content, respectively, for the two tests), in this case, the CHARPY had a better crushing strength, since the higher volatile content present in the CHAR leads to combustion in earlier stages.



**Fig. 7 – Average abrasion results for samples of burned pellets from the seven firing tests.**

The study by Tôrres et al. [7] showed success in reducing the percentage of pellets with less than 200 kgf/pellet, because of their hypothesis that a biomass fuel with a passing through 44  $\mu\text{m}$  of at least 87% could improve the distribution of energy inside a pellet during burning process.

### 3.6. Tumble and abrasion indices

The results of tumble index showed no significant variation. The values for tests 1, 2, 3, 5 and 7 were, respectively, 95%, 95%, 95%, 94.8% and 94.8%, thus, near each other and practically did not differ. The lowest values were for tests 4 and 6, 94.6% and 94.6%, respectively.

The values found for the average tumble index (% >6.3 mm) for the seven burnt pellets from the seven burning tests were similar to the values found in the literature Vale [13], LKAB [14], Umadevi et al. [15] and Geerdes et al. [16], with values of at least 93.5%, 94.0%, 95.5% and 95.0% respectively. In this way the values found for tumble of the analyzed samples are considered satisfactory.

On the other hand, the increase in the biomass ratio in the fuel mixtures tends to reduce the value of the tumble index, although in this study the reduction value was small (0.53% below the standard). In the present study, the results obtained were even lower than those found in Tôrres et al. [7], whose standard values and the worst result were 95.1% and 93.8%, respectively, a change of 1.47%.

In this study, AF had a positive effect on the tumble index, since its particle size passing through 44  $\mu\text{m}$  for AF1 and AF2 was 72.7% and 79.9%, respectively, in the same way as in Boechat's studies et al. [19] and [20] with passing through 44  $\mu\text{m}$  of 72% and 73%, respectively. It means an adequate size for AF when utilizing biomass.

Fig. 7 shows the average abrasion results for the samples from the seven firing tests.

With respect to abrasion, there is an upward trend as the levels of CHARs and CHARPYs are increased, since the addition of biomass tends to increase the abrasion rate, which is not of interest to the industry. However, when compared to the reference (test 1), although the results ranged from 3.7 to 4.4% for passing through 0.5 mm, all results are satisfactory since the results are close to the standard (test 1), it is possible to state that the general conditions of combustion were equivalent generating similar products.

However, it is important to emphasize the negative influence (in abrasion) of grain size coarser than 44  $\mu\text{m}$  of CHAR, since, from test 4 to test 6 (both CHARs), there was a decrease of passing through 44  $\mu\text{m}$ , of 86.9% (CHAR1) to 62.3% (CHAR2) as shown in figure. The same can be observed in the tests with CHARPY, whose levels passing through 44  $\mu\text{m}$  was 95% (CVRP1) to 67.1% (CVPR2).

The work of Geerdes et al. [16], LKAB [14] and VALE [13], adopts, as indicative of quality values passing through 0.5 mm maximum between 5 and 5.5%. Comparing with the present work, it is noticed that, in this issue, all the samples present better values than those made available by the international producers of pellets.

## 4. Conclusions

- The higher the volatiles content of a fuel, the hypothesis of thermal decomposition becomes more possible. It means that fuels with lower volatile matter as anthracite fines and CHARPY have lower possibility of degradation in smaller temperatures, therefore the burned pellet consolidation happens in similar conditions.
- Tests 1, 2, 3 and 5 were the best, and they showed that is possible to use the charcoal in pelletizing with a satisfactory quality results.
- Based on the results found in this study and when compared to the literature, it is concluded that both CHAR and CHARPY must have particle size less than 87.0% for 44  $\mu\text{m}$ . In this way a better distribution of energy inside the pellet, improving the burning and the physical properties of the pellets burned is possible.
- The use of charcoal and biomass at certain dosages may replace AF, but these fuels tend to worsen the values of tumble and abrasion indices with increasing CHAR or CHARPY dosages. That mechanism which leads to those worsening needs to be better understood.

## Conflicts of interest

The authors declare no conflicts of interest.

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