Combustion of high mesh content waste tires and coal for blast furnace injection via thermogravimetric analysis

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Abstract

In this study, the combustion characteristics of pulverized high mesh content waste tire and low-volatile coal were examined, along with the co-combustion behaviors of blends incorporating 5%, 10%, and 30% waste tire content. The primary objective was to assess their combustibility using a thermogravimetric analyzer, focusing on the potential for partially substituting pulverized coal (PCI) in blast furnaces. Additionally, the composition of the ashes from individual fuels and the higher heating value (HHV) of individual fuels and their blends were also determined. The ash composition analysis of waste tires revealed a predominance of iron and zinc, with low levels of alkalis and phosphorus. Generally, the co-combustion behaviors were consistent with the summation of the individual components. Notably, the tests showed that adding waste tires reduced the coal's ignition temperature. In the initial combustion stages, waste tire addition increased the degree of conversion, while sustaining this conversion in later stages, thus providing a combustion support effect. Among the tested blends, the 10% waste tire addition exhibited the best performance, balancing improved combustion behavior with adherence to ash content limits.

Keywords: Pulverized coal injection; Waste tire; Thermogravimetric analyzer; Blast furnace.

1 Introduction

In the context of the Brazilian ironmaking industry, all coal employed in the blast furnace route, including the pulverized coal injection (PCI) process, is importe [1] d. Thus, the costs, the foreign market and fossil fuel dependence increase. As such, the search for alternative national efficient and low-cost fuels has become the focus of study in lines of research to build concrete possibilities for overcoming these challenges.

Concurrently, the Brazilian automotive industry grapples with the challenge of effectively managing waste tires. Waste tires are characterized as those with irreparable damage to their structure, rendering them unsuitable for continued use in running or undergoing overhaul [2]. Currently, Brazil is the seventh largest car tire producer and the fifth truck/bus and van tire producer in the world, with approximately 68 million units of tires, considering replacement, assemblers and exports [3]. Thus, the high production of tires promotes a high generation of national waste tires. Between 2013 and 2019, the country annually produced more than 400,000 tons of waste tires [4]. However, the ramifications of the size and all the possible ways of disposing of waste tires in Brazil are still not measurable, as well as their use potential.

From these two scenarios, the utilization of waste tires via the PCI route emerges as a promising alternative to meet the ironmaking industry's demand for domestic, efficient, and cost-effective fuels, aiming to partially replace coal, while also contributing to new routes for the treatment of waste tires.

Due to reasons arising from the characteristics of the original tire and the routes on which it is treated, the waste tire is a fuel with heterogeneous characteristics. It is basically formed by a polymeric structure made up of various rubbers and additives; carbon black filler and inorganic meshes (metallic and textile). Its high organic content, linked to the high carbon content, generally gives the waste tire a high enough calorific value to guarantee a strong energy quality when used as fuel [5,6]. The rubber blends give the waste tire high concentrations of volatile material, and therefore, it is expected that it can contribute to improving the low volatile coal's combustibility and a more reactive chars generation during injection [7,8].

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The few existing studies have predominantly focused on waste tires derived from recycling routes involving intense pulverization, being practically pure rubber [9,10]. However, the current industrial scenario in Brazil involves high costs in producing such materials due to the high cost of the pulverization and inorganic content separation processes, with the output from recycling companies consisting mainly of tires with a high mesh content. So many waste tires have high levels of metallic and textile mesh. Its burning promotes high ash formation. The contents may vary the level of influence on the combustion behavior of the waste tire. The inorganic content of waste tires can significantly impact their combustion behavior. In general, a high ash content decreases both combustion efficiency and the thermal efficiency of the blast furnace due to its higher heat capacity and the formation of a molten ash layer on the surface of the solid residue after combustion.

While the study of waste tire behavior in a thermobalance [10-13] may appear extensively investigated, the reality is that the body of literature concerning the study of waste tire mixtures with pulverized coal, specifically targeting the PCI route, remains relatively sparse when compared to other routes such as coking and electric arc furnace routes. Moreover, when examining works regarding the methodological strategy, such as the comparison of higher heating value (HHV), levels of addition, characteristics of coals used in blends, among others, the literature is notably limited [14].

The objective of this research is to study the waste tire with a high mesh content combustion performance using the thermogravimetric analysis, in order to compare the waste tire and coal combustibility behavior.

In addition, the combustion behavior of waste tire and coal blends was determined, in order to know the effects of the residue addition on these behaviors and to evaluate the potential for future studies, aiming at the injection of these national, efficient and low-cost fuels in PCI.

2 Materials and methods

2.1 Materials

The waste tire with high mesh content came from batches supplied by a recycling company in Espírito Santo, Brazil. They went through a granulation process by cryogenic recovery, being received in granulometry below 600 µm. The coal used was a low volatile coal, of rank LBV [15], typically used in PCI, coming from a steel company. The coal was ground in the 75-25 µm range. 3 binary blends of coal and waste tire were produced, with 5%, 10% and 30% of waste tire addition level.

2.2 Chemical analysis and higher heating value determination

Proximate and elemental analysis were conducted according to ASTM D7582-15 [16] and ASTM D5373-93 [17], respectively. The ashes chemical composition o was determined using X-ray fluorescence (XRF) according to ASTM D4326-03 [18], using the RIGAKU ZSX Mini II equipment. The high heating value was determined according to ASTM D5865/D5865M-19 [19] in an IKA C200 bomb calorimeter.

2.3 Combustibility – TGA

The combustibility tests were carried out in a NETZSCH thermobalance, model STA 409 PC Luxx. In the tests, a sample mass of 20 mg was placed in the equipment's alumina crucible and the temperature was increased from 40 to 1000 °C at a heating rate of 20 °C/min and air flow of 100 mL/min.

From the combustion profiles, the reactivity, or apparent reaction rate, was determined, which measures the reagent consumption as a function of the reaction time. This rate was determined for each point along the temperature using Equation 1 [20].

$$R = -\frac{1}{w_0}\left(\frac{dw}{dt}\right) \tag{1}$$

where w_0 is the initial ash-free mass and dw/dt is the mass loss variation at time t.

The combustion profiles allowed evaluation of coals waste tire and blends combustibility through three characteristic parameters:

- Initial combustion temperature (T_i) – corresponds to the fuel ignition temperature, considered as the temperature at which the reaction rate corresponds to 1/5 of the maximum rate [21].
- Peak or maximum reaction temperature (T_p) - corresponds to the maximum reaction rate temperatures. In the waste tire case, these may present more than one region with different peak temperatures due to the different stages of tire combustion [11].
- Final or burnout combustion temperature (T_f) - temperature related to complete combustion, determined when the mass loss rate (DTG) is less than 1%/min [22].

In addition, the combustion profile was used to evaluate the degree of conversion of fuels and their blends at certain temperatures throughout their heating process.

The conversion degree was defined as the percentage of contribution to the combustion already carried out up to that temperature, and it is a parameter widely used in TGA studies on the injection of coal mixed with polymeric materials in PCI, including waste tires [8,13] (Equation 2).

$$\text{Degree conversion}(\%) = \frac{m_0 - m_i}{m_0 - m_f} \text{ X100} \tag{2}$$

where m_0 is the initial mass used, m_i the mass measured at a certain temperature, and m_f is the final mass after combustion.

Table 1. Proximate and ultimate analysis for individual fuels

Fuel	Proximate Analysis, %				Ultimate Analysis, % (db)				
	M	Ash (db)	VM (db)	Cfix (db)	C	H	N	Stot	O*
Coal (C)	1.64	9.04	15.58	75.39	93.4	4.33	1.74	0.34	0.2
Waste Tire (WT)	1.24	12.70	61.42	25.88	88.76	7.96	0.52	2.44	0.33

db: dry basis; M: moisture; VM: volatile matter; Cfix: fixed carbon; Stot: total suphfur content; O*: oxygen calculated by difference.

The chosen temperatures were 500, 600 and 700 ºC, as they represent, respectively, the moment before, during and after the combustion of the coal char.

3 Results and discussion

3.1 Chemical analysis – individual fuels

The proximate analysis and ultimate analysis for the two individual fuels are presented in Table 1.

The waste tire shows a volatile content four times higher than that of coal, due to the high concentration of rubbers and the blend of relatively lighter rubbers found in its organic structures. The coal ash content was close to 9% on a dry basis, below the 10% indicated as the limit for use in PCI. However, the waste tire showed a high ash content, which was higher than the maximum recommended limit for injection. It can be justified by the metallic mesh and the textile's significant presence in waste tire. The high levels can also explain the low fixed carbon content, which corresponds to the most resistant organic fraction of the tire, almost entirely associated with the carbon black presence, which is lower when compared to lower ash content waste tires [23] and presents an organic fraction that devolatilizes during heating [11].

The ultimate analysis revealed a high percentage of carbon content for coal, above 90%, and a low hydrogen content, close to 4%. High carbon contents are related to high calorific value and high substitution rate, low hydrogen contents can hinder physical aspects related to gas density and pressure in the combustion area, since lower hydrogen contents decrease the concentration of H_2, which is a less dense gas, in addition to being a more energy efficient reducer than CO, presenting a less endothermic iron ore reduction reaction. The waste tire presented a higher hydrogen content, which can be associated with the higher volatile content. In addition, it presented relatively lower levels of carbon, but this is still high when compared to other fuels [24], including some high volatile coals [25]. It also presented a lower nitrogen content than coal, which indicates that its combustion in blends with coal can result in lower NOX emission levels. However, the high sulfur content of the waste tire could be a challenge, resulting from the vulcanization process.

For a clearer understanding of the presence of other elements in waste tires, Table 2 displays the composition of both coal ash and waste tire samples.

Coal ash is primarily composed of SiO_2, Al_2O_3, Fe_2O_3, and CaO, giving it an overall acidic nature [26]. In contrast, waste tire ash contains significant levels of Fe_2O_3, ZnO, and SiO_2, with the latter linked to reinforcing fabrics in rubber [27]. Fe_2O_3 is beneficial for injection, adding iron to the blast furnace and supporting the metallurgical process. However, high ZnO content can be problematic, as it may increase emission of zinc-rich gases, posing environmental risks due to toxicity and potential biocontamination of ecosystems [28]. In the blast furnace, ZnO may also contribute to damage to refractory linings and furnace walls. Lower phosphorus content in waste tire ash is a positive factor, as high phosphorus levels weaken steel and are difficult to eliminate in the reducing atmosphere of the blast furnace. On the positive side, waste tires have lower alkali content compared to coal, benefiting blast furnace operations. Reduced presence of oxides like K_2O and Na_2O helps minimize recirculation, slag formation, and degradation of refractories and coke [29].

Table 2. Main components of the ash from individual fuels

Fuel	Composition, %	
	C	WT
SiO_2	44.20	10.92
Al_2O_3	29.07	0.85
Fe_2O_3	7.99	48.17
ZnO	-	33.41
MgO	1.82	-
MnO	0.09	0.25
CaO	5.39	1.95
K2O	1.00	0.60
Co_2O_3	-	0.53
P_2O_5	2.38	0.35
TiO_2	1.61	-
SO_3	2.57	1.77
CuO	-	1.20
Alkali*	0.10	0.08
Phosphorus**	0.23	0.04
Basicity***	0.20	1.80

*Represents the alkali content ($K_2O + Na_2O$) in coal (%); **Represents the phosphorus content (P_2O_5) in coal (%); ***Ratio between the sum of the molar fraction of basic oxides (Fe_2O_3, CaO, MgO, K_2O, and Na_2O) and the sum of the molar fraction of acidic oxides (Al_2O_3 and SiO_2).

3.2 Chemical analysis – blends

The proximate analysis for waste tire and coal blends are presented in Table 3.

Almost all the chemical properties of the blends proved to be additive. As waste tire addition level increased,

Table 3. Proximate analysis for blends

Blends	Composition	Proximate Analysis, %			
		M	Ash (db)	VM (db)	Cfix (db)
WT_5%	95% C + 5% WT	1.77	9.06	17.67	71.51
WT_10%	90% C + 10% WT	1.72	9.34	19.91	69.03
WT_30%	70% C + 30% WT	1.59	11.12	28.56	58.73

db: dry basis; M: moisture; VM: volatile matter; Cfix: fixed carbon

there was a tendency for the blend ash content to increase, exceeding the recommended limit for PCI at the addition level of 30%. Therefore, this addition level is undesirable for injection. However, all the other addition levels showed an ash content within the adequate range for injection, since the relatively lower ash content of coal made it possible to mix up to the 10% waste tire addition level.

There was a tendency for the volatile content of blend to increase as the tire was added, which has a negative aspect for injection, since it can cause caging and load lowering, as well as promoting a greater burn temperature reduction [26]. However, the value should not exceed 40%, considered the volatile matter limit for coal, due to the high rank of the coal used. The increase in the volatile content of coal, when within the limit, tends to improve coal burnout to O_2 [27], as well as to generate more reactive chars to CO_2 after burning in the combustion zone [28].

3.3 Higher heating value determination

The waste tire addition level effect on waste tire and coal blends higher heating value (HHV) behavior is shown in Figure 1.

Analyzing the curve of real values, both individual fuels and blends exhibited an HHV above 30 MJ/kg, which aligns with the recommended values for PCI fuels (25). WT exhibited the highest HHV at 33.780 MJ/kg, while coal's HHV was 31.812 MJ/kg. It can be observed that the blends HHV increases as the level of addition of waste tires in the mixture increases. This may be linked to the combustion support effect commonly seen in the combustion of organic fuels with high volatile content when blended with pulverized coals [8]. Although there is a difference with the values calculated by the average of the individual fuels, it is not possible to conclude additive behavior within the studied range.

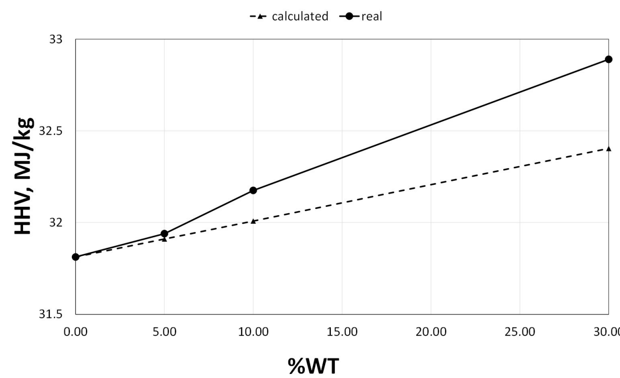

Figure 1. Waste tire addition level effect on HHV.

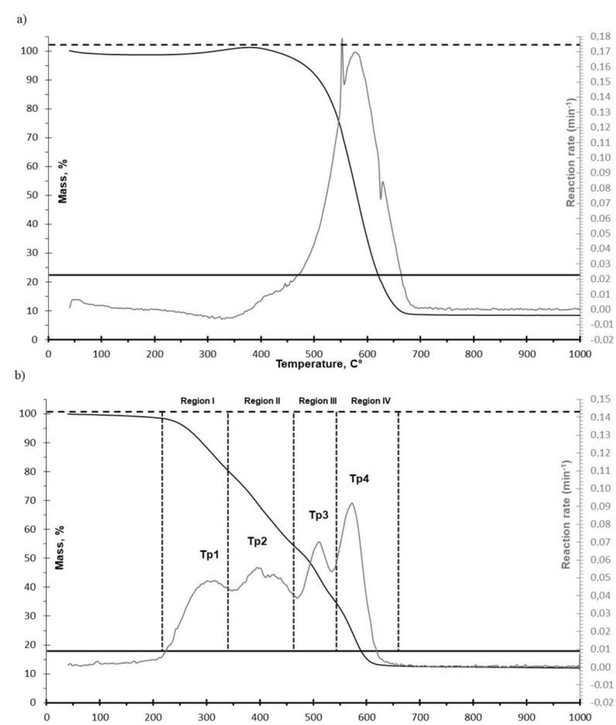

Figure 2. Combustion behavior of (a) coal C and (b) waste tire WT.

3.4 Combustibility – combustion profiles

3.4.1 Individual fuels combustion

The TGA curves and the reaction rate behavior, derived from the DTG curves, as a function of temperature for the individual fuels are shown in Figure 2.

The material's low moisture content implies small step of mass loss at the beginning of the test. The coal mass increase between 200 and 400 °C is associated with the chemisorption phenomenon, where oxygen present in the air used as a carrier, can deposit on the coal surface just before reacting, particularly in areas with smaller pores, resulting in a significant increase in mass [21,30].

The coal's high ignition temperature is associated with the low combustibility of coal, generally increasing with increasing rank [31]. The region of increased mass loss just after ignition indicates the release and combustion of volatiles. At a temperature close to 550 °C, there is an acceleration of mass loss, indicating the consumption of fixed carbon, associated with the combustion of the char generated after the release of volatiles [30].

The peak temperature (Tp) was close to 576 °C, considered quite high when compared to lower rank coals, and is associated with lower combustibility due to its low volatile content and generation of less reactive chars. The peak on the left side of the maximum rate reaction peak corresponds to some type of coal contamination that was consumed, possibly originating from oxidation over time. This observation was made by comparing with other curves from the same sample in previous periods, where this peak was not present. As it does not correspond to the original sample, this peak was disregarded in the reaction rate analysis.

In the waste tire combustion profile, four reaction regions were identified: region I – degradation of waste tire's basic components; region II – primary devolatilization of waste tire's polymeric content; region III – secondary devolatilization of waste tire's polymeric content and waste tire char formation; region IV – tire char combustion. For WT, the peak temperatures for regions I, II, III, and IV were 317.52 °C, 396.10 °C, 510.93 °C, and 572.79 °C, respectively. WT had an ignition temperature lower than coal, indicating that the tire starts combustion more quickly, which may indicate a greater reactivity of these fuels compared to high-rank coals, mainly due to the higher volatile content and the high amount of basic components and rubbers with lower degradation temperatures [7,10].

In region I, the peak corresponds to the degradation of plasticizers, oils, additives and other basic components of the tire, with lower molecular mass, which are the first to be consumed [9,12]. In region II, the peak is primary devolatilization of the tire's polymeric structure, releasing lighter gases such as CO, CO_2, H_2O, CH_4, alkanes and alkenes of 2 to 3 carbons. The peak in region III corresponds to the secondary devolatilization of the polymeric structure, with the degradation of the heaviest constituents of the less resistant rubbers that were not devolatilized, such as natural rubber (NR), and to a greater degree the degradation of constituents of the most resistant rubbers, such as butadiene rubber (BR) and styrene butadiene rubber (SBR), which degrade at intermediate (420-470 °C) and elevated (470-530 °C) temperatures [32]. Finally, in region IV, char combustion occurs, which presented the highest maximum reaction rate, due to high carbon concentration in remaining organic fraction that will react with oxygen of reactive atmosphere.

The existence of several tire-degradation regions is one of the reasons for the lower maximum reaction rate for tire char combustion in region IV when compared to coal char combustion. Another justification is that the more metallized characteristics of the tire could be the reason why its high content of matter of inorganic origin could have absorbed the heat supplied during heating and reduced the reaction rates. For PCI applications, the high ash content of additives directly affects the stability and combustion efficiency of the blast furnace [33,34]. Another reason may be the particle size of the fuels. It is known that reducing the particle size of coals can substantially improve their combustion performance, due to favoring kinetic phenomena and a decrease in the thermal gradient of the surface in relation to the center of the particle, increasing burnout [15,35].

3.4.2 Blends co-combustion

The reaction rate behavior, derived from the DTG curves, as a function of temperature for the blends are shown in Figure 3.

The blend's co-combustion behavior corresponded to the sum of the individual combustion behaviors of their individual constituents. The blend's combustion showed a region referring to the initial devolatilization of the waste tire (200-500 °C), and another referring to the devolatilization of coal and the combustion of the chars generated by both fuels (500-700 °C). The first region was predominantly driven by tire addition, corresponding to its main devolatilization regions, and the second was governed mainly by coal, corresponding to its oxidation region of the char generated [36,37].

The average parameters obtained from the blend curves are shown in Table 4.

In general, there was a tendency to reduce the ignition temperature of blends with the increase waste tire level addiction. This demonstrates that, even with larger particle sizes and high ash contents, the high amount of energy released by the polymeric fraction of the tire particles contributed to accelerate the combustion process of the pulverized coal [7,8,10]. In the higher temperature region, there were no significant differences in peak temperatures between coal and blends. This is directly related to the combustion support effect on coal, since, in addition to improving coal ignition, the maintenance of the peak temperatures is a strong indication that there was no coal combustion reduction during char oxidation for all waste tire levels.

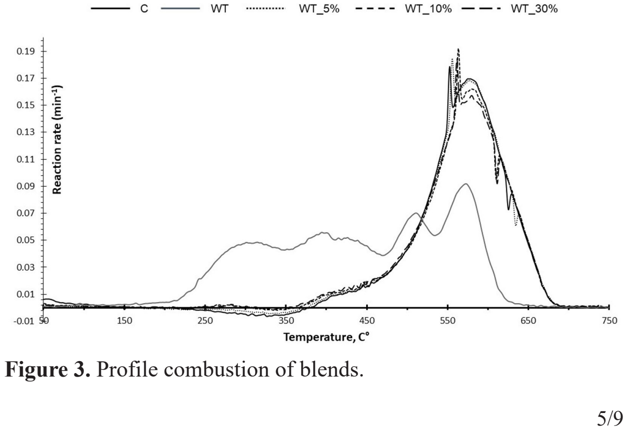

Figure 3. Profile combustion of blends.

Table 4. Average parameters obtained from the blends

	C	WT_5%	WT_10%	WT_30%
Ti (°C)[a]	487.02	487.32	483.39	473.32
Tp (°C)[b]	576.16	576.81	575.99	576.71
Rmáx (min^{-1})[c]	0.1664	0.1657	0.1600	0.1414
Tf (°C)[d]	669.65	672.67	670.96	664.45
mresidual (%)[e]	10.21	12.61	10.87	11.18

[a]Ignation temperature; [b]Peak temperature; [c]Maximum reaction rate; [d]Final or burnout temperature; [e]Residual mass after combustion.

Even with similar peak temperatures, there was a significant reduction in the maximum reaction rate with 30% level addition. This effect may be associated with the high ash content of the tire, where from a certain level of addition, the material of inorganic origin in the tire ends up reducing the amount of energy available for the combustion of coal char. However, for the 5 and 10% level addiction, no differences in the rate were identified, which indicates that the addition of the tire was not enough to affect the combustion support behavior at these levels. This is a positive factor to evaluate the feasibility injection of waste tires in PCI.

3.4.3 Combustibility – conversion degree

The conversion degree profile and the average conversion degree referring to temperatures of 500, 600 and 700 °C, of individual fuels and blends, are shown in Figure 4 and Table 5, respectively.

During blend combustion, the waste tire's high heat of combustion originating from the high amounts of volatiles up to 500 °C, ended up being absorbed by the pulverized coal, generating an increase in the heat accumulated by the coal. This resulted in an increase in the degree of inflection of the curves in this blend region, approaching the degree of coal conversion.

The support effect generally increased with the tire addition level increase, significantly improving the coal combustion behavior.

In this way, it is expected that in blends, the coal reaches the accumulated heat higher than the heat of dissipation before the time that individual coal would obtain, anticipating the ignition [8,13,38].

It is expected that, in initial moments, the incomplete combustion of waste tire portion in blends, promotes a greater release of CO and other volatiles in relation to the original coal, improving the speed of coal combustion. From the figure, we could identify significant differences in the degree of conversion up to the 500 ºC temperature from 10% waste tire addition, which is in accordance with the increase in the inflection of the curves, indicating that the waste tire determined the combustion in that period, acting in fact, as anticipators of the reaction from that level of addition.

However, in the later period, there is a tendency for waste tire devolatilization to deplete. As waste tires do not have a high fixed carbon content, the conversion degrees become lower due to the low content of organic matter

Table 5. Conversion degree of individual fuels and blends

Fuel	Conversion degree (%)		
	500 °C	600 °C	700 °C
C	9.14	73.08	99.57
WT	60.64	96.37	99.53
WT_5%	9.47	70.12	99.79
WT_10%	12.28	71.79	99.71
WT_30%	21.51	75.83	99.42

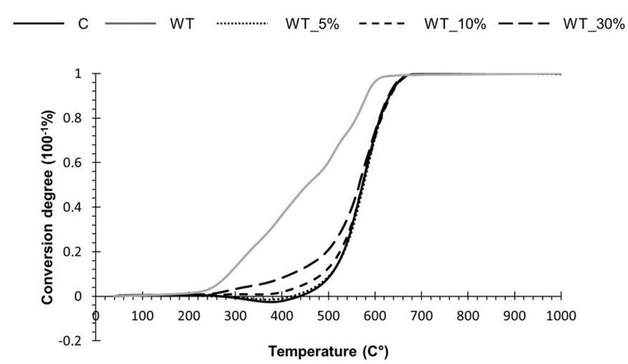

Figure 4 - Conversion degree profiles of individual fuels and blends.

remaining to react after the initial moments of combustion. Specifically tires with high ash content would still contribute to combustibility reduction in this region due to the absorption of energy by matter of inorganic origin. Thus, combustion in this period would be determined by coal combustion, indicating the probable inability of waste tire to improve the pulverized coal combustibility. However, this did not imply that the tire sample studied in this research did not present high enough reactivity to continue the combustion, in order to guarantee the maintenance of the coal combustion behavior [8].

For 5% waste tire addition blends, there was no improvement in the degree of coal conversion, with greater difficulty in supporting combustion due to the low contribution of volatiles compared to the other levels. As for 30%, the best behavior of the degrees of conversion during heating was contacted, due to the high contribution of volatile in generating chars of more reactive coals. However, at this level of addition, the blend has a high ash content, which exceeds the specified blast furnace limit [29]. In this way, the waste tire addition of 10% is the one that presented the best balance, since it contributes to the improvement of the combustion behavior and does not exceed the limit of the required ash content.

Adding waste tire pulverized to coal in PCI can increase the coal combustion rate and the degree of conversion during ignition and generate chars that guarantee combustion support in the final stages of the process. This analysis is in line with what was found in thermobalance tests where the viability of adding low ash waste tires content to coal for PCI was evaluated [8].

4 Conclusion

- The ash composition analysis of waste tires showed a predominance of iron and zinc, with lower levels of alkalis and phosphorus.
- Except for the waste tire addition of 30%, all the blends presented ash content within the appropriate range for injection.
- There is an increase in the coal HHV as the level of addition of scrap tires in the mixture increases.
- In general, there was a tendency to reduce the ignition temperature of coal with the increase waste tire level addition, that indicates higher combustibility.
- The blends' combustion behavior corresponded to the sum of the individual combustion behaviors of their individual constituents. The blends' combustion was controlled by the waste tire in the volatile release region, and by coal in the char oxidation region.
- The association of the high volatile content released from the unserviceable tire and the high reactivity of its chars promoted the support effect of coal's char combustion, increasing the conversion degree in the initial moments, and ensuring the maintenance of the conversion degree in the final moments of combustion.
- The waste tire addition of 10% is the one that presented the best balance, since it contributes to the improvement of the combustion behavior and does not exceed the limit of the required ash content.

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References

1 Instituto Aço Brasil. Anuário estatístico 2021. Rio de Janeiro: IABR; 2021 [cited 2022 Jan 22]. Available at: https://acobrasil.org.br/site/wp-content/uploads/2021/07/Anuario_Completo_2021.pdf

2 Brasil. Conselho Nacional do Meio Ambiente – CONAMA. Resolução nº 416 de 30 de setembro de 2009. Diário Oficial da União. 2009 [cited 2021 Mar 30]. Available at: http://www2.mma.gov.br/port/conama/legiabre.cfm?codlegi=616

3 Associação Nacional da Indústria de Pneumáticos – ANIP. Relatório: vendas totais de pneumáticos (reposição + montadoras + exportação) 2020. São Paulo; 2021 [cited 2021 Mar 29]. Available at: https://www.anip.org.br/sitenovo/wp-content/uploads/2021/02/Vendas-totais.pdf

4 RECICLANIP. Volume de pneus destinados. 2021 [cited 2021 Mar 30]. Available at: https://www.reciclanip.org.br/destinados/

5 Díez C, Martínez O, Calvo LF, Cara J, Morán A. Pyolysis of tyres. Influence of the final temperature of the process on emissions and the calorific value the product recovered. Waste Management. 2004;24(5):463-469. http://doi.org/10.1016/j.wasman.2003.11.006.

6 Dourado DC, Rabelo GF, Schirmer WN, Stroparo EC, Barsi FV, Trugilho PF. Determinação do poder calorífico e análise elementar de pneus automotivos inservíveis. Espacios. 2018;39(4):20-35.

7 Li X, Ma B, Xu L, Hu Z, Wang X. Thermogravimetric analysis of the co-combustion of the blends with high ash coal and waste tyres. Thermochimica Acta. 2006;441(1):79-83. http://doi.org/10.1016/j.tca.2005.11.044.

8 Zhang J, Ren S, Liu Z, Zhou Y, Meng F, Su B. Combustion-supporting effect of common carbonous solid waste on anthracites. Journal of the Minerals Metals & Materials Society. 2012;64(8):1011-1016. http://doi.org/10.1007/s11837-012-0391-4.

9 Leung DYC, Wang CL. Kinetic study of scrap tyre pyrolysis and combustion. Journal of Analytical and Applied Pyrolysis. 1998;45(2):153-169. http://doi.org/10.1016/S0165-2370(98)00065-5.

10 Pan D, Jiang W, Guo R, Huang Y, Pan W. Thermogravimetric and kinetic analysis of co-combustion of waste tires and coal blends. ACS Omega. 2021;6(8):5479-5484. http://doi.org/10.1021/acsomega.0c05768.

11 Atal A, Levendis YA. Comparison of the combustion behaviour of pulverized waste tyres and coal. Fuel. 1995;74(11):1570-1581. http://doi.org/10.1016/0016-2361(95)00122-L.

12 Conesa JA, Font R, Fullana A, Caballero JA. Kinetic model for the combustion of tyre wastes. Fuel. 1998;77(13):1469-1475. http://doi.org/10.1016/S0016-2361(98)00068-4.

13 Yan B, Zhang J, Guo H, Liu F. Research on simultaneous injection of waste tires with pulverized coal for blast furnace. In: Matyáš J, Ohji T, Pickrell G, Wong-Ng W, Kanakala R, editors. Advances in materials science for environmental and energy technologies IV. Beijing: The American Ceramic Society; 2015. p. 135-144.

14 Lima GPK. Caracterização e avaliação do comportamento de combustibilidade de pneus inservíveis e suas misturas com carvão mineral em termobalança visando à injeção em altos-fornos [dissertação]. Porto Alegre: Programa de Pós-graduação em Engenharia de Minas, Metalúrgica e de Materiais (PPGE3M), Universidade Federal do Rio Grande do Sul; 2022.

15 Fragoso HP, Pohlmann JG, Machado JGMS, Vilela ACF, Osório E. Combustion behavior of granulated and pulverized coal in a pci rig: combustibility and pressure variation analysis. Journal of Materials Research and Technology. 2019;8(6):1-6. http://doi.org/10.1016/j.jmrt.2019.09.055.

16 American Society for Testing and Materials – ASTM. ASTM D7582-15: standard test methods for proximate analysis of coal and coke by macro thermogravimetric analysis. West Conshohocken: ASTM; 2023.

17 American Society for Testing and Materials – ASTM. ASTM D5373-93: standard test methods for instrumental determination of carbon, hydrogen, and nitrogen in laboratory samples of coal and coke. West Conshohocken: ASTM; 2017.

18 American Society for Testing and Materials – ASTM. ASTM D4326-03: standard test method for major and minor elements in coal ash by X-ray fluorescence. West Conshohocken: ASTM; 2021.

19 American Society for Testing and Materials – ASTM. ASTM D5865/D5865M-19: standard test method for gross calorific value of coal and coke. West Conshohocken: ASTM; 2019.

20 Ollero P, Serrera A, Arjona R, Alcantarilla S. Diffusional effects in TGA gasification experiments for kinetic determination. Fuel. 2002;81(5):189-200.

21 Alonso MJG, Borrego AG, Alvarez D, Kalkreuth W, Menéndez R. Physicochemical transformation of coal particles during pyrolysis and combustion. Fuel. 2001;80(13):1857-1870. http://doi.org/10.1016/S0016-2361(01)00071-0.

22 Morgan PA, Robertson SD, Unsworth JF. Combustion studies by thennogravimetric analysis - 1. Coal oxidation. Fuel. 1986;65(11):1546-1551. http://doi.org/10.1016/0016-2361(86)90331-5.

23 Martínez J, Puy N, Murillo R, Garcia T, Navarro M, Mastral A. Waste tyre pyrolysis: a review. Renewable & Sustainable Energy Reviews. 2013;23(1):179-213. http://doi.org/10.1016/j.rser.2013.02.038.

24 Campos AMA, Novack K, Assis PS. Selection of materials for blast furnace injection using quality indicators. Metals and Materials. 2019;72(1):119-123.

25 Fragoso HP. Avaliação da combustibilidade de carvões em simulador de PCI: evolução da metodologia de operação [dissertação]. Porto Alegre: Programa de Pós-graduação em Engenharia de Minas, Metalúrgica e de Materiais, Universidade Federal do Rio Grande do Sul; 2019.

26 Riley J. Routine coal and coke analysis-collection, interpretation, and use of analytical data. West Conshohocken: ASTM International; 2007.

27 Zhang G, Wang F, Dai J, Huang Z. Effect of functionalization of graphene nanoplatelets on the mechanical and thermal properties of silicone rubber composites. Materials. 2016;9(2):92. http://doi.org/10.3390/ma9020092.

28 Veres J, Lovás M, Jakabksý S, Sepelák V, Hredzák S. Characterization of blast furnace sludge and removal of zinc by microwave assisted extraction. Hydrometallurgy. 2012;129-130:67-73.

29 Carpenter AM. Use of PCI in blast furnaces. London: IEA Coal Research; 2006.

30 Crelling JC. Coal combustion under conditions of blast furnace injection. In: Proceedings of the Ironmaking Conference; 1995; Nashville. Warrendale: ISS; 1995; p. 73-79.

31 Lima GPKL, Fragoso HAP, Pohlmann JG, Vilela ACF, Osório E. Comportamento de carvões na combustão visando PCI e sua relação com as características químicas, físicas e petrográficas. In: Anais do 50º Seminário de Redução de Minério de Ferro e Matérias-Primas e 8º Simpósio Brasileiro de Aglomeração de Minério de Ferro - ABM Week 6ª edição; 2021; São Paulo. São Paulo: ABM; 2021. p. 10.

32 Pohlmann JG, Osório E, Vilela ACF, Diez MA, Borrego AG. Pulverized combustion under conventional (O_2/N_2) and OXY-FUel (O_2/CO_2) conditions of biomasses treated at different temperatures. Fuel Processing Technology. 2017;155:174-182. http://doi.org/10.1016/j.fuproc.2016.05.025.

33 Carpenter AM, Skorupska NM. Coal combustion: analysis and testing. 1st ed. London: IEA Coal Research; 1993. (Série IEACR).

34 Ghetti P. DTG combustion behaviour of coal: correlations with proximate and ultimate analysis data. Fuel. 1986;65(5):636-639. http://doi.org/10.1016/0016-2361(86)90356-X.

35 Williams P, Besler S. Pyrolysis-thermogravimetric analysis of tyres and tyre components. Fuel. 1995;74(9):1277-1283. http://doi.org/10.1016/0016-2361(95)00083-H.

36 Kurose R, Ikeda M, Makino H. Combustion characteristics of high ash coal in a pulverized coal combustion. Fuel. 2001;80(10):1447-1455. http://doi.org/10.1016/S0016-2361(01)00020-5.

37 Hutny WP, Lee GK, Price JT. Fundamentals of coal combustion during injection into a blast furnace. Progress in Energy and Combustion Science. 1991;17(4):373-395. http://doi.org/10.1016/0360-1285(91)90008-B.

38 Vamvuka D, Schwanekamp G, Gudenau HW. Combustion of pulverized coal with additives under conditions simulating blast furnace injection. Fuel. 1996;75(9):1145-1150. http://doi.org/10.1016/0016-2361(96)00029-4.

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