The effect of briquette composition on coking pressure generation
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ABSTRACT

A coal normally used in coking blends was employed to study the effect of briquettes on coking pressure. The study is focused primarily on two parameters i) bulk density which increases with the use of briquettes and ii) the composition of the briquettes containing materials which have contrary effects on coking pressure. Four briquettes with different compositions were prepared, two of them containing biomass. A non-coking coal and coal tar as binder were included in the composition of all four briquettes. The permeability of the plastic phase to gas flow was studied for blends of coking coal with individual briquette components and for blends of coking coal with 15 wt% of the four briquettes. The coking pressure was measured in a movable wall oven and the mechanical strength, coke reactivity and post-reaction strength of the cokes were assessed by means of standard tests, JIS, CRI/CSR. It was found that all four briquettes produced lower coking pressure than that generated by the coking coal regardless of the increase in bulk density while the cokes retained their quality up to 15 wt% briquette addition.

Keywords: biomass, briquettes, coke quality, coking pressure

1. Introduction

The intensive consumption of fossil fuels by the steel industry is causing significant environmental problems associated with the emission of CO₂ and the resulting greenhouse effect [1]. Although steel can be produced by electric arc furnaces, nowadays most of the steel is produced in integrated factories that use blast furnaces as opposed to direct reduction processes and electric arc furnaces [1]. Metallurgical coke is used in blast furnaces as a fuel, a reductant, a support for the charge and a provider of its permeability [2]. In order to be able to accomplish these tasks, coke needs to be of adequate quality, which in general terms is measured by its strength and reactivity and determined by the raw material and coking conditions [2]. In the preparation of metallurgical coke, various additives apart from coking coal can be used and have an influence not only on the quality of the product but also on the process itself [2–4]. Biomass has been studied in recent years as an additive to coking blends with the aim of reducing CO₂ emissions and also to extend the use of alternative raw materials in cokemaking [5–8]. When studying the inclusion of biomass in coking blends, it is important to evaluate not only the effect on coke quality but also on the process itself. Specifically, this includes the modification of the coking pressure that might arise from resistance to the escape of volatile matter generated during the process as excessive coking pressure may cause operational problems and damage to the oven wall. Various factors affect the generation of coking pressure, such as the intrinsic characteristics of the coal, coking conditions (i.e. bulk density etc.) and the use of additives [2,9,10]. In order to counteract the decrease in bulk density produced by the inclusion of biomass in coking blends, the use of briquettes has been proposed as their incorporation would increase the bulk density and compensate for any reduction in density due to the use of biomass. The higher bulk density values would also help to counteract the decrease in coke quality [11,12]. The effect of additives on coking pressure depends on their characteristics. Thus coke fines, sawdust and anthracite tend to reduce coking pressure

whereas bituminous additives increase it [13–15]. In light of this, the study of the effect of briquettes prepared with coal tar as binder and sawdust is interesting considering the effects of these briquette components on the development of coking pressure. Research studies published to this point have focused on the study of the effect of additives in binary blends. In the present research work, blends made up of three/four components: a dangerous coal, biomass, non-coking coal and a bituminous binder have been investigated. The principal aim of this study is to analyze the effect that briquettes containing biomass, non-coking coal and coal tar as binder have on the development of coking pressure during co-carbonization in a movable wall oven of 17 kg capacity. The effect on the coke quality is also studied as an additional aim.

2. Experimental

2.1. Briquette preparation and material characterization procedures

The briquettes were prepared using a low volatile non-coking coal (C) and a sawdust from chestnut (SC) obtained as a waste from the timber industry. Coal tar (T) was used as binder for the preparation of the briquettes. For comparison purposes the dangerous coal used as base (Coal A) was included in the composition of two briquettes. The composition of the briquettes is shown in Table 1. They were prepared using a roll press briquetting machine with a capacity of 5 t/h. The briquettes were ellipsoid shaped with axes 46 mm and 42 mm in length and weighing around 23 g.

Elemental analysis was carried out following ISO 562 and ISO 1171 for humidity, ash and volatile matter, respectively. For the elemental analysis the following were used: ASTM D 5016-98 and ASTM D 5373-02 for C, H and N and using LECO CHN-2000 and LECO S-144 DR instruments for sulphur. Table 2 shows the main characteristics of the materials used and particle size distributions.

2.2. Permeability of coal plastic phase

Binary blends of the coal A with 2.25 wt% of sawdust, 2.25 wt% of C and 2.25 wt% of T were tested. The amount added i.e. 2.25 % represent the amount of T and SC in

the case of 15 wt% briquette addition. The non-coking coal C is present in the blends in a higher proportion depending on the type of briquette added but the same percentage was tested in order to facilitate comparison. In addition, mixtures of coal A with 15 wt% of each briquette were tested in order to evaluate the effect of the additives on the permeability to gas flow of the coal plastic phase. A representative sample of 2 g ground to < 3 mm was placed in a cylindrical quartz tube of 20 mm internal diameter. The height of the coal bed was 10 mm. A layer of alumina was placed at the top and bottom of the coal bed in order to ensure uniform heating and to prevent the scattering of fine coal particles. The samples were heated up to 800 °C at a heating rate of 3 °C/min and nitrogen was introduced from the bottom of the coal layer at a flow-rate of 0.01 m/s [16]. Changes in pressure (ΔP) during heating were measured every 30 s. The permeability was evaluated from the pressure drop caused by a forced inert gas flow through the plastic coal layer. The Darcy law relates the permeability to pressure drop and ΔP will be used in the present research paper as a representation of the permeability of the coal bed. The tests were carried out a minimum of three times.

2.3. Carbonization experiments and coke quality evaluation

The carbonization tests were carried out in a movable wall oven of approximately 17 kg capacity (MWO17) [17]. The dimensions of the oven are 250 mm L x 165 mm W x 790 mm H. A load cell was mounted on the movable wall to measure the force exerted on the wall during carbonization. A programmable controller was used to control the oven temperature. The temperature at the centre of the coal charge was monitored by means of a thermocouple connected to a computer. The coal was top-charged using a hopper after the oven had reached 1100 °C. The temperature of the wall was kept constant throughout the test. The coke was pushed out 15 min after the centre of the charge had reached 950 °C. Coking lasted approximately 3.5 hours. The cold mechanical strength of the cokes produced was assessed by the JIS test (JIS K2151). After the test, the coke was sieved and the DI150/15 index was calculated from the amount of coke with a particle size greater than 15 mm. Coke reactivity and mechanical strength after reaction

were assessed by means of the NSC test (ASTM D5341). Two indices were derived from this test i.e. the CRI index representing the loss of weight of a 200 g sample of coke with a size between 19-22.4 mm after reaction with CO₂ at 1100 °C for two hours and the CSR index representing the percentage of partially-reacted coke remaining on a 9.5 mm sieve after 600 revolutions in a standardized drum. The relationship between the CSR values obtained in a MWO of 17 kg capacity and those obtained in a MWO of 300 kg has been reported previously [18]. The CRI indices should be in the range of 20– 30% and the CSR indices, above 60% [19]. The repeatability limit of this method for CRI is 2.0 and for CSR is 2.5. It is considered that the lower the CRI and the higher the CSR, the better the quality of the coke.

2.4. Textural characterization of the cokes

The particle size selected to determine the porous structure of the materials was between 1 and 3 mm. The samples were degasified under vacuum at 200 °C for 24 h prior to adsorption to eliminate all the moisture and condensed volatiles.

The true density (ρ_{He}) of the chars was measured by means of helium pycnometry in a Micromeritics Accupyc 1330 Pycnometer [20]. Their apparent density (ρ_{Hg}) was determined with mercury at 0.1 MPa in a Micromeritics autopore IV 9500 mercury porosimeter. From the true and apparent densities, the open porosity and total pore volume corresponding to pore sizes smaller than 12 μ m were calculated by means of the following equation:

$$\varepsilon(\%) = \left(1 - \frac{\rho_{Hg}(g/cm^3)}{\rho_{He}(g/cm^3)} \right) \cdot 100 \quad (1)$$

The total pore volume (V_T) was obtained from the equation:

$$V_T (cm^3 / g) = \left(\frac{1}{\rho_{Hg}(g/cm^3)} - \frac{1}{\rho_{He}(g/cm^3)} \right) \quad (2)$$

The pore size distribution was calculated by applying increasing pressure to the sample from 0.1 to 227 MPa. This resulted in pore sizes in the range of 12 μm to 5.5 nm as determined by the Washburn equation:

$$d_p \text{ (nm)} = \frac{1244}{P(\text{MPa})} \quad (3)$$

Pore size was classified into three categories: macropores ($12 \mu\text{m} > d_p > 50 \text{ nm}$), mesopores ($50 \text{ nm} > d_p > 5.5 \text{ nm}$) and micropores ($d_p < 5.5 \text{ nm}$). In order to determine the microporous structure of the cokes, physical adsorption of CO_2 at 273 K was carried out in a Nova 4200e Quantachrome Instruments. The Dubinin-Radushkevich (D-R) equation was then applied to the CO_2 adsorption isotherms in order to obtain the volume of micropores (W_0) and the characteristic adsorption energy (E_0). Following the procedure of Stoeckli [21] the E_0 was related to the average width of the micropores (L), while the surface area of the micropores (S_{mi}) was related to the volume W_0 by means of the following empirical equations:

$$L(\text{nm}) = \frac{10.8}{E_0 (\text{kJ/mol}) - 11.4} \quad (4)$$

$$S_{mi}(\text{m}^2/\text{g}) = \frac{2000 \cdot W_0(\text{cm}^3/\text{g})}{L(\text{nm})} \quad (5)$$

3. Results and discussion

3.1 Permeability of the plastic layer

The measurement of the permeability of the plastic phase to gas flow has been related to the development of coking pressure in the literature [22–24]. In the present research work, binary blends of coal A with sawdust, T and the non-coking coal C were tested as a first approach towards understanding the results of the complex blends that made up the briquettes. The pressure drop with temperature is shown in [Figure 1a](#). In

addition mixtures of coal A with 15 wt% of the four briquettes were also tested and the results are shown in [Figure 1b](#). The parameters obtained from the curves as defined in a previous paper [16], i.e. temperature of the initial decrease in permeability (T_{ini}), temperatures T_1 and T_2 that correspond to the beginning and end of the low permeability zone and the maximum pressure drop (ΔP_{max}), are shown in [Table 3](#). The temperature of the beginning of the reduction of permeability is similar for all the samples which reflects the great influence of the base coal on this parameter. Binary blends and the mixture A15B3 show a low permeability zone (i.e. range T_2-T_1) and ΔP_{max} similar to that of coal A. In contrast, these parameters are clearly influence by the presence of the other briquettes.

Although, the ability of the additives to increase the permeability of the plastic zone is not clear with small percentages of addition (i.e. 2.25%), there is no doubt that with larger percentages of addition (briquette addition), they increase the permeability drastically ([Figure 1b](#)). It is the ability of tar to cause a decrease in the viscosity of coal in its plastic state that is probably responsible for the ability of this binder to reduce the ΔP_{max} [25–27]. This binder is highly aromatic and contains compounds that stabilize the radicals formed during the decomposition of coal, which enhances the thermoplastic properties of coal [28,29].

At the temperature of the beginning of the reduction of the permeability ($T_{ini}=429$ °C) tar conversion is around 90% (see [Figure SM1](#)), whereas at T_2 (the temperature of the end of the low permeability zone) tar conversion is around 95 %. Although most of the tar devolatilization occurs before the plastic stage, this binder is able to maintain the fluid H% and the mobility of the fluid phase up to 500 °C [27].

The greatest difference in permeability compared to that of coal A is shown by the blends with briquettes B1, B2 and B4 ([Figure 1b](#)). Although briquette B2, contains 35 wt% of the dangerous coal A, it reduces ΔP drastically, probably due to the presence of SC, since the analogous briquette without sawdust (i.e. B3) is unable to reduce the ΔP curve.

Chestnut sawdust decreases coal fluidity, while at the same time increasing the gas permeability of the coal's plastic layer [30]. **Figure SM1** shows that when the coal reaches the temperature at which the reduction of the permeability begins ($T_{ini}=429\text{ }^{\circ}\text{C}$) the initial sawdust has already been transformed into a char that reduces fluidity because it adsorbs the products of coal devolatilization and its abundant porosity allows the gases to evolve more easily [30]. Nevertheless, the addition of 2.25% of SC does not cause any significant modification of the ΔP curve, in agreement with the findings of a previous work on the direct addition of sawdust [30] (**See Figure 1a**). The modification of the ΔP curve is clearly observed in the case of the briquette blends. To understand why SC does not produce a significant change in the ΔP curve, two effects need to be considered: on the one hand a reduction in fluidity (i.e. an increase in viscosity) contributes to the obstruction of the flow of gas through the coal plastic phase, whereas the porosity of the sawdust char facilitates it. It is possible that when the small amount of SC is used (2.25 wt%) the increase in viscosity is predominant. In the case of the briquettes the amount of inerts is greater and so the effect of porosity predominates.

The devolatilization of coal C occurs in the same temperature range as coal A (**see Figure SM1**). Coal C is a non-coking coal, therefore, it does not pass through a plastic stage, so it remains in as a solid during the plastic stage of coal A, which facilitates the evolution of gases. Furthermore, coal C reduces the fluidity of coal A but not as much as sawdust, so the effect of porosity is predominant in this case [31].

3.2. Carbonization in the movable wall oven (MWO)

The individual coal A and its blends with 10 and 15 wt% added briquettes B1 and B2 were carbonized, in the case of briquettes B3 and B4 because no biomass was included in their composition and the effect on quality was thought to be less deleterious, tests with up to 20 wt% additions were carried out. The bulk density of the charge in the carbonization oven (i.e. mass charged per unit volume) is an important operational factor in cokemaking which influences throughput, coking pressure and coke quality [2].

Generally speaking, it is influenced by the particle size distribution and the moisture content of the coal. The particle size of the coal used was kept constant in all the carbonization tests, as was the moisture content of the charge (i.e. 5 wt%). The use of briquettes produced an increase in the bulk density of the charge and was used to compensate for the decrease in coke quality when the blend included additives such as non-coking coal or biomass [2,11]. **Figure 2** displays the variation in the bulk density of the charge with the addition of briquettes. The individual coal A was carbonized in the movable wall oven at a bulk density of 784 kg/m^3 on a dry basis (db). It can be seen from the graph that the increase in addition produced an increase in bulk density although no differences were observed between the different briquettes for the same level of addition. The increase in bulk density is linearly related to the amount of briquettes in the blend for additions between 10 and 20 wt% ($R^2=0.982$). The variation of the coking pressure during the carbonization test is shown in **Figure 3** for coal A and its blends with 15 wt% of briquettes B1, B2, B3 and B4. It is known that the coking pressure curves measured in movable wall ovens are very variable. Nevertheless four main types are the most frequent [2]. The curve corresponding to coal A is of type 2 which is characterized by a first phase showing a maximum and a second phase with an even more pronounced maximum. In general, the shape of the curves corresponding to the blends of A and 15 wt% of the briquettes is also of type 2 but with a lower maximum coking pressure value. It is generally accepted that bulk density plays a very important role maximizing coking pressure. For instance an increase of 25 kg/m^3 can produce a coking pressure 50 % higher [2]. The variation in coking pressure with the amount of briquettes added is shown in **Figure 4**. The briquettes contain various materials that produce contrasting effects. On the one hand, biomass and non-coking coal produce a decrease in coking pressure [14,17] while on the other hand, coal tar increases it [2,32,33].

Sawdust and non-coking coal used in the preparation of briquettes decrease coking pressure due to the so-called 'Inert-effect' because they remain solid when the high coking pressure coal is in its plastic state and facilitate the escape of gas, which

decreases the internal gas pressure [34]. In the case of the coal tar used as binder, it is generally accepted that it increases coking pressure due to the accumulation of tar in the cold side of the oven which in turn increases the amount of volatiles and the aggregation of the coal. This is a consequence of the lateral heating in slot-type ovens that produce two plastic layers that move inwards from the oven walls and meet at the center of the oven [35].

From the results shown in [Figure 4](#) it is clear that the carbonization with all the briquettes produces lower coking pressure than coal A when carbonized alone, [in agreement with the permeability results \(Figure 1b\)](#). The increase in the amount of briquettes in the blend produces a decrease in the coking pressure except for the addition of 20 wt% of B3 and B4 probably because at this percentage of addition, the decrease in coking pressure due to the biomass and non-coking coal cannot compensate for the effect of the coal tar and the bulk density. The decreasing effect of the biomass and the low volatile non-coking coal is due to the fact that when the high coking pressure coal is in its plastic state these additives act as inerts that facilitate the escape of the gas. B1 and B2 produce the greatest effect whereas B3 that contains coal A in its composition has the least effect. The briquettes that contain biomass (i.e. B1 and B2) produce a reduction of around 45 % in coking pressure at 10 wt% addition, even in the case of briquette B2 which contains coal A in its composition. Accordingly, briquettes B1 and B2 produce an important reduction of ΔP_{max} in the permeability test. In the case of B3 which also contains coal A, the reduction in coking pressure is lower, around 24 %. Also, B3 produces the lowest reduction in ΔP_{max} . The greater reduction in the case of B2 can be attributed to the sawdust. A similar conclusion can be derived from the comparison between B1 and B4. The presence of sawdust produces a greater effect on coking pressure than the non-coking coal, in agreement with the results obtained in the permeability test.

After blend composition, the bulk density of the charge has the biggest effect on the pressure developed during coking, an exponential relationship has been established between the two parameters [2]. Taking into account the important effect of bulk density on coking pressure, these variables have been plotted in [Figure 5](#). Although the bulk density in the carbonization test of coal A is similar to those of the carbonizations of coal A with 10 wt% of the four briquettes, the coking pressure generated is lower. Moreover, further increases in bulk density do not translate into increases in coking pressure. The inert effect of the non-coking coal and the sawdust facilitating the escape of the volatile matter and decreasing coking pressure predominates over the effect of the bulk density.

In order to be able to compare these results with the direct addition of chestnut sawdust [14] it should be noted that the addition of 15 wt% of B1 and B2 represents a 2.25 wt% of sawdust in the blend. The direct addition of this amount of sawdust leads to a reduction in bulk density, whereas in the case of the addition of briquettes an increase in bulk density occurs that is not reflected by an increase in coking pressure. On the contrary the coking pressure generated with an addition of 15 wt% of B1 and B2 is similar to that obtained with the direct addition of the equivalent amount of sawdust [14]. Nevertheless, it should be considered that the amount of dangerous coal in the blend with the addition of briquettes is lower than with the direct addition of sawdust.

No direct linear relationship was found between maximum pressure drop ($\Delta P_{\max}$) and coking pressure measured in the movable wall oven. Indicating that the permeability measured in the laboratory does not directly predict the coking pressure as measured in the movable wall oven. Various papers have been published that investigate the relationship between $\Delta P_{\max}$ and coking pressure and although permeability obviously has some influence on coking pressure no direct relationship has been found [22,36].

3.3. Coke quality

The use of briquettes is only feasible if their effect on coke quality is minimal. The quality of the cokes produced in the MWO was evaluated by means of the standard tests described in the experimental section. **Figure 6** shows the variation in the JIS indices with the amounts of the four briquettes. The DI150-5 index (**Figure 6a**) indicates that the addition of B1, B2 and B4 produced an increase in the generation of fines during the experiment, especially in the case of 15 wt% addition of B1 probably due to the presence of sawdust, for which integration into the coke matrix is the worse. In the case of the addition of B3 the presence of a greater percentage of coal A helps to preserve coke quality and size. The increase in the bulk density with 15 wt% addition (**Figure 2**) also helps to produce a slightly smaller amount of fines in the case of B3. In the case of index DI150-15, the effects which are similar can be summarized as follows: i) The best results were obtained with B3, which both for 10 and 15 wt% additions produced slightly higher indices than the coal (2.3 and 1.1 points respectively) ii) 10 wt% additions of B1, B2 and B4 produced similar values in the 71-73 range. The presence of the coking coal (B1 vs B2 and B3 vs B4) in the briquettes is beneficial for mechanical strength when no biomass is included in the briquettes.

Nowadays the CSR index is considered as the most representative and widely used for determining coke quality. The linear relationship between CSR and CRI is generally accepted although some authors have reported the contrary [37]. It is considered that a good quality coke should have a CSR higher than 60 [19], although Nomura [38] has suggested that a coke with higher reactivity could improve the efficiency of the blast furnace. **Figures 7a and 7b** display the variation in the CRI and CSR indices respectively with the amounts of briquettes added. The results obtained are very similar in the case of the cokes obtained with 10 and 15 wt% addition regardless of the type of briquette used, a difference of around one point in CSR. Compared to the coke from the coal A, the addition of up to 15 wt% produced a reduction of around 3 points in the CSR. The addition of 20 wt% of briquettes produced a decrease of around 3 points in the CSR

compared to 15 wt%. The results are similar to those obtained with the direct addition of 3 wt% of sawdust [14]. Although the use of these briquettes implies addition of up to 10.5 wt% of non-coking coal apart from the sawdust in the case of B1.

The porous structure of the cokes and the composition of the ashes are two main factors that explain the CSR indices [19]. In the present research work, data obtained for the pore size distribution and surface area are presented in Table 4. The porosity and pore volume corresponding to the pores < 12 μm , in the cokes obtained with a 15 wt% addition of the four briquettes are very similar to those of the coke from coal A. The porosity ranges from 29 to 33 % and the total volume from 0.21 to 0.25 cm^3/g . Our results show no variation in the porosities calculated from the true and apparent densities determined with He and Hg, respectively. Results from the literature show an increase in porosity of around 6 % for cokes prepared with 15 wt% of briquettes containing a similar biomass [11]. In general, no direct relationship was established between the porous structure and the indices derived from the drum tests. Only a relationship between coke tensile strength and porous structure could be established from image analysis [39]. Table 4 also includes the pore size distributions and no great differences are apparent. Cokes prepared with briquette additions all have lower percentages of macropores (i.e. pores >50 nm) which can be attributed to the greater bulk density. A slightly higher percentage of micropores (pores <5.5 nm) is also observed in the case of cokes prepared with briquettes which can be attributed to the presence of inerts in the briquettes due to their poorer integration than inherent inert in the coke matrix [40]. In the case of sawdust (i.e. cokes A15B1 and A15B2) the surface area of micropores (S_{mi}) is around 80 m^2/g , which are slightly higher compared to the value of the coke from the coal A (23 m^2/g).

The important role of mineral matter in coke and its influence on coke performance in the blast furnace has been generally accepted in recent years. Alkali metal content can be a major impediment when selecting coals, particularly in the case of Na and K that are considered to act as catalysts of carbon gasification in the blast

furnace, seriously altering its function, since an increase in ash basicity has a catalytic influence on coke reactivity [19,41,42]. Sawdust has low ash content compared to coals A and C used in the present research paper (Table 2). The composition of the ashes is shown in Table 5 together with the definition of the alcalinity index (AI). Nevertheless, the composition of the sawdust ashes which have higher percentages of basic oxides, (especially K_2O and CaO) and lower percentages of acidic oxides (Al_2O_3 and SiO_2) gives rise to a AI index higher than that of coal A. In the case of coal C its AI index is also higher than that of coal A but in this case it is due to the high amount of Fe_2O_3 and low amount of SiO_2 . The two inert materials contained in the briquettes (i.e. sawdust and non-coking coal C) have a high value of AI which is bound to have a negative effect on coke reactivity (CRI index). Taking into account the composition of the briquettes (Table 1), the ash composition (Table 5) and proximate analysis of the coal A and the briquette components (Table 2), the volatile matter, ash and AI indices of the briquettes and the blends of coal A with 15 wt% of B1 to B4 have been calculated (Table 6). Tar was not taken into consideration due to its low ash content and its consistent percentage in all the briquettes studied (15wt%). Compared to B3 and B4, briquettes B1 and B2 have a lower percentage of ash (around 7.5 wt%) and higher of volatile matter (around 32 wt%) due to the presence of sawdust. Consequently, the amount of coke from the briquettes will be higher in blends with B3 and B4. No great differences are apparent in the alkalinity indices of the four briquettes, the greatest difference being 0.36 between B1 and B3. As a consequence, the characteristics of the blends of coal A and 15 wt% of the four briquettes are very similar (Table 6). The results shown in Figure 7 indicate that the cokes produced from blends of coal A and the four briquettes are similar (differences of one point in CSR for cokes produced with blends of A and 15 wt% of the four briquettes) which is consistent with the results of the AI and surface area that serve to explain reactivity values.

5. Conclusions

The effect of using briquettes on coking pressure and coke quality was studied.

Our results show the following:

1. Coking pressure decreases with all of the briquettes tested and at various levels of addition.
2. Although the pressure drop is not highly affected by any single additive, blends of coal A with the briquettes produce differences in this value. The temperature range of low permeability is always lower than the corresponding range for coal A alone.
3. The increase in bulk density due to the use of briquettes does not imply an increase in coking pressure.
3. The positive effect of bulk density on coke quality allows the inclusion of a greater amount of additives like non-coking coal apart from sawdust.
4. The use of briquettes in percentages of up to 15 wt% produces a diminution of coking pressure of up to 50 % with a decrease of only 3 points in CSR.

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Table 1. Briquettes composition expressed in wt%.

	B1	B2	B3	B4
T	15.0	15.0	15.0	15.0
SC	15.0	15.0	-	-
C	70.0	35.0	42.5	85.0
A	-	35.0	42.5	-

Table 2. Main characteristics of the raw materials.

	T	SC	C	A
Ash (wt% db)	0.8*	1.3	10.2	10.1
Volatile matter (wt% db)	67.9*	78.5	14.5	17.4
C (wt% db ^a)	90.3	48.7	80.8	80.6
H (wt% db ^a)	4.7	5.6	4.0	4.1
N (wt% db ^a)	0.8	0.5	1.7	2.0
S (wt% db ^a)	0.38	<0.05	0.45	0.61
O ^b (wt% db ^a)	3.9	42.3	2.9	2.2
> 3 mm (wt%)	-	1.0	20.3	13.8
2-3 mm (wt%)	-	4.5	12.6	13.1
1-2 mm (wt%)	-	24.6	16.8	14.8
0.5-1 mm (wt%)	-	65.8	22.7	15.7
< 0.5 mm (wt%)	-	4.1	27.6	43.5

*: Determined in a thermobalance. ^a: Dry basis. ^b: Calculated by difference.

Table 3. Parameters obtained from permeability test.

	$\Delta P_{\max}^a$ (mbar)	Stand. Dev $\Delta P_{\max}$	T_{ini}^b (°C)	$T1^c$ (°C)	$T2^c$ (°C)	$T2-T1$ (°C)
A	99	5	429	466	495	33
A2.25T	83	13	429	468	496	28
A2.25SC	101	9	427	464	494	30
A2.25C	93	8	426	468	494	26
A15B1	24	10	430	476	499	23
A15B2	59	8	428	475	497	22
A15B3	85	13	424	466	493	27
A15B4	40	12	428	469	495	26

^a $\Delta P_{\max}$: Maximum value of pressure drop.

^b T_{ini} : Temperature of the beginning of the reduction of the permeability coefficient.

^c $T1$, $T2$: Temperatures of the beginning and end of the low permeability zone.

Table 4. Textural characteristics of cokes from coal A and their blends with 15 wt% of the four briquettes.

Sample	$\rho_{\text{Hg}}^{\text{a}}$ (g/cm ³)	$\rho_{\text{He}}^{\text{b}}$ (g/cm ³)	V_{T}^{c} (cm ³ /g)	ϵ^{d} (%)	$V_{\text{macro}}^{\text{e}}$ (%)	$V_{\text{meso}}^{\text{f}}$ (%)	$V_{\text{micro}}^{\text{g}}$ (%)	S_{mi}^{h} (m ² /g)
A	1.35	1.91	0.22	30	54	3	43	23
A15B1	1.34	1.89	0.21	29	51	3	46	83
A15B2	1.29	1.89	0.25	32	45	3	53	82
A15B3	1.29	1.91	0.25	33	40	3	57	18
A15B4	1.35	1.93	0.22	30	47	3	50	46

^a: Apparent density. ^b: True density. ^c: Total pore volume (pores < 12 μm). ^d: Open porosity (pores < 12 μm). ^e: Macropore volume (12 μm < pores size < 50 nm). ^f: Mesopore volume (50 nm < pore size < 5.5 nm). ^g: Micropore volume (pore size < 5 nm). ^h: Micropore surface area.

Table 5. Ash composition and alkalinity index of coals and sawdust.

Sample	Fe ₂ O ₃ (wt%)	Mn ₃ O ₄ (wt%)	CaO (wt%)	MgO (wt%)	SiO ₂ (wt%)	Al ₂ O ₃ (wt%)	P ₂ O ₅ (wt%)	SO ₃ (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)	TiO ₂ (wt%)	AI (%)
A	4.56	0.14	1.13	0.59	60.12	29.90	0.82	0.19	0.73	1.09	0.66	0.91
SC	3.18	--	41.21	3.79	28.38	7.10	1.72	--	0.60	4.09	0.29	1.94
C	7.32	0.15	2.66	1.45	46.06	35.38	1.74	1.26	0.67	1.38	1.89	1.69

$$AI = Ash \circ \frac{(Fe_2O_3 + MgO + CaO + Na_2O + K_2O)}{(SiO_2 + Al_2O_3)}$$

Table 6. Characteristics of the briquettes, and the blends of coal A with 15 wt% of the four briquettes.

	B1	B2	B3	B4	A15B1	A15B2	A15B3	A15B4
Ash (wt% db)	7.5	7.4	8.7	8.8	9.7	9.7	9.9	9.9
VM (wt% db)	32.1	33.1	23.7	22.5	19.6	19.8	18.3	18.2
AI (%)	1.47	1.20	1.11	1.44	0.99	0.95	0.94	0.99

db: dry basis. AI: alkalinity index.

Figure 1. Variation of pressure drop with temperature, a) binary blends of coal A with sawdust (SC), non-coking coal (C) and tar (T) and b) with 15 wt% of the four briquettes.

Figure 2. Variation of bulk density with briquette addition.

Figure 3. Variation of coking pressure with time for coal A and its blends with 15 wt% of four briquettes.

Figure 4. Variation of maximum coking pressure with briquette addition.

Figure 5. Variation of coking pressure with bulk density of the charge.

Figure 6. Variation of mechanical strength of cokes with the amount of briquettes.

Figure 7. Variation of CRI/CSR indices with the amount of briquettes.