1 EFFECT OF SAWDUST ADDITION ON COKING PRESSURE PRODUCED BY TWO
2 LOW VOL BITUMINOUS COALS

3 L. Florentino-Madiedo, D. Casal, E. Díaz-Faes, C. Barriocanal*

4 Instituto Nacional del Carbón, INCAR-CSIC, Apartado 73, 33080 Oviedo. Spain

5 *Corresponding author. Tel: +34 985 11 90 90; Fax: +34 985 29 76 62; e.mail address:

6 carmenbr@incarcsic.es
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8 ABSTRACT
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11 Two high-rank bituminous coals and three sawdusts of different origin were selected to
12 study the effect of biomass on coking pressure. The effect of the biomass on the
13 thermoplastic properties of the coals was assessed by means of the Gieseler test. In
14 addition, the effect of the biomass on the thermal decomposition of the coals was studied
15 by means of thermogravimetric analysis together with the modification of the permeability
16 of the coal plastic phase. The individual coals and the blends were carbonized in a 17
17 kg movable wall oven; the coking pressure developed was measured and the quality of
18 the resulting coke was assessed. It was found that the sawdust reduced coking pressure,
19 especially in the case of the coal that developed the highest coking pressure. This effect
20 was attributed to the modification of the permeability of the plastic phase to gas flow. It
21 was concluded that although the addition of sawdust produces a decrease in coking
22 pressure, additions should be limited to small amounts to avoid excessive deterioration
23 of the quality of the product.
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27 Keywords: Coal, biomass; coke, coking pressure, permeability, thermogravimetric
28 analysis

1. Introduction

The inclusion of biomass in coking blends has been increasingly investigated in recent years with a view to widening the range of alternative raw materials that can be included in coking blends [1-6]. One of the reasons for using biomass is the general concern about the generation of greenhouse gases resulting from the use of fossil fuels and the high consumption of coal in the steel industry [7-9]. When using additives, it is important to bear in mind the influence they have on coal thermoplasticity and on coke quality [10-12]. Another important cause for concern when including an additive in a coking blend, is the modification of the coking pressure that may be caused by the additive. The structure of a coke oven is not very strong and even the application of relatively low pressure may result in deformation and damage to the walls of the oven and shorten its life span with considerable economic loss for the coking industry. The phenomenon of coking pressure generation is complex and several different processes play a role at the same time. Coal devolatilization, fluidity, permeability of the plastic mass to the gas flow, resolidification of the coal mass, semicoke porosity and fissuring are all factors that are involved in the phenomenon of coking pressure generation [13-16].

During coking the oven walls are maintained at a high temperature (1300 °C), throughout the process so that, when the coal is charged into the oven, a temperature gradient appears in the coal charge. This means that layers of coke, semicoke and coal are present at the same time in the oven extending from the wall to the centre i.e. from the hottest to the coolest part of the oven. Heat is then gradually transferred inwards and, as the coal layer reaches its softening temperature, the volatile products that start to evolve and escape can either pass into the already formed semicoke or condense on the coal. At this point the permeability of the plastic coal to gases is of great importance because this is the factor that determines whether the evolved gases escape or whether they remain entrapped in the plastic layer [17-20]. Furthermore, internal gas pressure is considered by some authors [19] to depend on the permeability of the plastic layer to the

flow of gas and on the rate of gas evolution inside this layer. Also worth noting is that the escape of gases through the semicoke layer seems to depend not only on the type of pore structure but also on the fissure pattern, since these fissures provide pathways for the gases to escape through [21].

The coals that generate high coking pressure are usually high rank bituminous coals that tend to produce good mechanical strength coke and in high yields. However, the use of these coals in coking blendings may give rise to operational problems that must be controlled by blend optimization, by modifying the coking conditions or by using additives.

The use of additives modifies the coking pressure generated during coking [22-25]. Inert material such as coke fines or non-coking coals will modify the viscosity of the coal plastic phase and the permeability of the charge to gases. In addition the final contraction and resolidification process will undergo modification. Waste plastics such as polyolefins produce an increase in the coking pressure due to modification of the thermoplastic properties, permeability and the H donor/acceptor reactions of the coal during co-carbonization [12,26]. Although the possibility of using biomass as an additive in coking blends has been studied its effect on coking pressure has not yet been reported.

The aim of the present study is to determine the effect of sawdust on the coking pressure generated by two low-volatile matter coking coals and on the quality of the resulting coke in order to determine the optimal amount of sawdust that can be added in order to avoid the deterioration of the quality of the coke.

2. Experimental

2.1. Materials and methods

Waste chestnut (SC), pine (SP) and oak (SR) sawdusts and two low volatile matter content bituminous coals (C1 and C2) were selected as materials for the experiments. The sawdusts were obtained as wastes from flooring industries. The moisture of the sawdusts was around 5 wt.%. Pine sawdust was torrefied (SPT) in a

rotary oven at 300 °C in order to reduce its oxygen and volatile matter content. Proximate analyses were performed following the ISO562 and ISO1171 standard procedures for volatile matter and ash content, respectively. An elemental analysis was carried out using a LECO CHN-2000 for C, H and N, a LECO S-144 DR for sulphur and a LECO VTF-900 for the direct determination of oxygen.

2.2. Assessment of coal thermoplastic properties

The thermoplastic properties of the coals and of the blends containing 1, 2, 3 and 5 wt% of each sawdust were measured by means of the Gieseler test (ASTM D2639-74). A 5 g sample with a size < 0.425 mm was heated, while a constant torque was applied to a stirrer placed inside the crucible containing the coal charge. The parameters measured by this test were: (i) softening temperature, T_s ; (ii) the temperature of maximum fluidity, T_f ; (iii) resolidification temperature, T_r ; (iv) plastic range, $T_r - T_s$, which is defined as the difference between the resolidification and softening temperatures; and (v) maximum fluidity, MF, expressed as dial divisions per minute (ddpm).

2.3. Thermogravimetric analysis and permeability measurement.

The TG/DTG analyses were carried out in a TA Instruments SDT 2960 thermoanalyzer. Samples of 10 mg sized to < 0.212 mm were heated at a heating rate of 3 °C/min up to 1000 °C. A nitrogen flow of 100 ml/min was maintained during the experiment to avoid oxidation and to remove the pyrolysis products. The derivative of the weight loss (DTG) was calculated from the TG data. The temperature of maximum volatile matter evolution (T_{max}) was obtained from the DTG curves.

The experimental procedure followed to measure the permeability of the coal plastic phase has been explained previously [14]. Briefly, a representative coal 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. The coal samples were heated up to 1000 °C at a heating rate of 3 °C/min and nitrogen was fed in from the bottom of the coal layer at a flow-rate of 0.01 m/s. Changes in pressure during heating were measured

every 30 s and the permeability coefficient K of the coal's plastic layer was estimated in accordance with Darcy's rule. The experiments were performed at least twice.

2.4. Carbonization experiments and coke quality evaluation

The carbonization tests were carried out in a movable wall oven of approximately 17 kg capacity (MWO17) [24]. 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 with a hopper when 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 standard procedure). 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. The coke reactivity and mechanical strength after reaction were assessed by means of the NSC test (ASTM D5341 standard procedure). 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 [27].

3. Results and discussion

The two coals selected were bituminous low volatile matter content coals with high carbon (>80 wt% db) and low sulphur (<0.7 wt% db) contents. Coal C2 with a higher C/H atomic ratio can be considered to have a higher degree of aromaticity (Table 1). In contrast the three sawdusts used have a high volatile matter content and low C and high

O contents. The C/H atomic ratios of the sawdust are lower than those of the coals, the lowest being that of the SP. The C/O atomic ratios of the coals are more than 20 times higher than those of the sawdusts. The sulphur contents are very low (< 0.02 wt %) in all three sawdusts. As expected, torrefaction of the pine sawdust (SP) produced an increase in the C/O atomic ratio due to the elimination of oxygen from the structure of the sawdust. The particle sizes of the coals and the sawdusts are also included in Table 1. The two coals were ground to obtain similar particle size distributions, whereas the sawdusts were left unground. The biomass was used as received. The finest biomass samples were oak, 79 wt.% of whose particles were smaller than 0.5 mm whereas the coarsest particle size distribution was that of SC, 4 wt.% of whose particles were smaller than 0.5 mm.

3.1. Effect of biomass on coal thermoplastic properties

Some coals when heated in the absence of air soften at around $400\text{ }^{\circ}\text{C}$ and their particulate state is then transformed into a fluid after which they are finally converted into a coherent mass at around $500\text{ }^{\circ}\text{C}$ (semicoke). It is during this temperature range that most of the coal volatile matter is evolved. Coal plastic properties are known to play a major role in the development of coking pressure [13-15]. Coals that generate a high coking pressure are usually referred to as dangerous coals, while those which do not develop high coking pressures are called safe. As is well known, there is no single coal property that can be used to predict the dangerousness of a coal. Nevertheless dangerous coals in general have a low fluidity. Coal fluidity varies as a function of rank due to variations in the molecular structure of the coal. For coals with a volatile matter content of around 30 wt% db fluidity is very high and it decreases with increasing rank due to the aromatization of the coal structure [15]. The coals used in the present research work are bituminous high rank and have a low fluidity with values of 233 and 34 ddpm for C1 and C2, respectively. As reported previously, the use of sawdust as an additive to coal produces a decrease in coal fluidity [3,4]. In this study the variation in fluidity was tested considering its importance in relation to coking pressure and to see whether there

is any relation between fluidity and devolatilization and the permeability of the plastic phase to the flow of gas. Figure 1 shows the loss of maximum Gieseler fluidity with increasing amounts of the three sawdusts and torrefied pine sawdust. The effect is similar in all three cases. No appreciable differences can be assigned to a particular type of sawdust or to the torrefied sawdust. Considering that a finer particle size of inerts leads to a greater reduction in fluidity, the differences observed between SC and SR, both of which are hardwoods, can be assigned to the fact that SR has greater proportion of particles smaller than 0.5 mm prior to grinding for the Gieseler test as required by the standard norm. Nevertheless it appears that the lower fluidity coal (C2) is more affected and for the same amount of sawdust the reduction in fluidity is greater. It can be seen in Figure 1 that 2 wt.% addition of SP produces reductions in Gieseler maximum fluidity of 36 and 55 % for C1 and C2 respectively. In a previous work the greatest reduction was obtained with a high volatile coal by adding torrefied oak sawdust [3]. Other authors have also found by means of SAOS rheometry that pine sawdust even in additions of only 2 wt.% has a deleterious effect on coal fluidity [11].

3.2. Thermogravimetric analysis of blends of coal and sawdust.

The thermal decomposition of the blends of coal and sawdust at 3 °C/min in a nitrogen atmosphere is shown in Figures 2 and 3. An increase in the content of sawdust in the blends leads to a lower coke yield due to the difference in the amount of volatile matter in the coals and the sawdusts. The difference between SP and SPT can be clearly appreciated in the TG/DTG curves in the inset in Figure 2. The char yield increases from 18.8 % for SP to 25.4 % for SPT and only two devolatilization steps are visible due to the decomposition of the cellulose and lignin in SPT. The DTG curves corresponding to co-pyrolysis clearly reflect the devolatilization steps of the sawdust and the coal. The low temperature peak in the DTG curve corresponding to the sawdust at around 341 °C increases as the percentage of sawdust in the blend increases. Similar findings can be deduced from Figure 3. As the amounts of the three sawdusts increase, so do their devolatilization peaks. In the DTG curves of the blends the peaks corresponding to the

decomposition of hemicellulose and cellulose are easily appreciated in the nine blends of coal C2 with the three sawdusts. To determine whether there was a synergistic effect during the co-pyrolysis, the calculated yield assuming additivity can be plotted against the experimental yield in the case of the blends and the result can be adjusted to a line with a correlation coefficient (r^2) of 0.937 (See Figure 4). These results together with those of the graphs in Figures 2 and 3 in which the devolatilization steps in the blends occur at the same temperature as in the pyrolysis of the coals and sawdusts suggest no interactions took place during the process.

3.3. Variation of the permeability of the coal plastic phase to the flow of gases due to the effect of sawdust addition.

The generation of coking pressure during coking has been related in the literature to various factors, most of which depend on the characteristics of the coal [15,22]. The permeability of the coal plastic phase to gases is one of these factors. In order to explain the effect of sawdust on the coking pressure developed by coal C2, the variation in the permeability of the coal plastic stage to the flow of gas was studied. Figure 5 shows the curves corresponding to the variation of the logarithm of the permeability coefficient (K) with temperature for coal C2 and its blends with the three sawdusts. The permeability coefficient remains constant up to around 440 °C, at which point it starts to decrease. There is then a plateau of low permeability, after which it increases as the coke resolidifies. The parameters derived from the test are included in Table 2. The value obtained for K in the case of the single coal C2 is similar to others reported in the literature [14,28]. When sawdust is used, the value of K does not show any significant variation. The most notable variations correspond to the value of the temperature at the end of the low permeability zone (T₂). All the blends show a T₂ which is at least 10 °C lower than that of the individual coal. As a consequence the low permeability range is also narrower than that of the single coal. Smaller ranges of low permeability are associated with a lower coking pressure.

3.4. Coking pressure

In the present work a semi-pilot scale (17 kg capacity) movable wall oven was used to determine coking pressure. Coals are considered to be dangerous, if the coking pressure measured in such an oven is higher than 15 kN/m². [24,27]

Figure 6 shows the variation in coking pressure against the increase in the amount of sawdust and torrefied sawdust. The point at 0 % addition corresponds to the coking pressure developed by the single coal. Coal C1 can be considered to be at the limit of dangerousness, while coal C2 is clearly dangerous. The addition of sawdust produces a decrease in the coking pressure in both coals. No important differences were observed between the three sawdusts or the torrefied sawdust, although, as can be seen in Figure 6, the coking pressure values corresponding to the torrefied sawdust are consistently lower than those of the corresponding blends including the non-heat treated sawdust and the oak sawdust (SR) produced a slightly more marked reduction in coking pressure than pine (SP) or chestnut (SC). The bulk density of the carbonization is considered to be one of the most important controlling factors of the development of coking pressure of a specific coal [15]. The use of sawdust in coking blends produces a decrease in the bulk density of the oven charge. In the carbonization of C1 the dry bulk density decreases from 776 kg/m³ to 760 kg/m³ and to 768 kg/m³ with 5 wt% addition of SP and SPT, respectively, whereas in the case of C2 the dry bulk density falls from 784 kg/m³ to an average value of 763 kg/m³ with the addition of 5 wt% of the three sawdusts. It is important to determine, however, whether the effect of the sawdust on coking pressure is due to its effect on the charge bulk density or to its effect on the permeability of the plastic phase to the flow of gas. Nomura et al. working with a low volatile coking coal of different particle sizes assigned the effect on coking pressure to the modification of the permeability of the plastic layer [29]. The results of the present research work also confirm that it is the presence of sawdust that modifies the permeability of the coal plastic layer with a consequent reduction in the coking pressure in the oven.

Biomass torrefaction produces changes that entail densification, lower O/C and H/C atomic ratios and a more uniform material that is easier to handle [30]. The more marked reduction in the case of torrefied sawdust can be assigned to the larger percentage of material present during the plastic and post-plastic stages of the coal resulting from the loss of volatiles during torrefaction. The coke yield at 500 °C in the case of SP is 23.5 %, whereas it is 33.6 % for SPT.

The reduction in coking pressure is more pronounced in the case of the coal that develops the higher coking pressure i.e. C2. For this coal the decrease in coking pressure is more marked up to 3 wt% addition with a decrease from 40 kPa to around 16 kPa (the average of the value obtained for the three sawdusts) which represents a reduction of 59 %. Similarly 2 wt% addition entails a reduction in the coking pressure generated by coal C2 of 40 %.

Given the influence of inherent large inerts on coking pressure since their high porosity helps the volatiles evolved from coal to escape, the sawdusts were subjected to SEM to study their porous structure. Figure 7 shows images of the three sawdusts together with the torrefied pine sawdust. SR and SC are both hardwoods and, as such, they have pores of different sizes that appear either separately or in groups. The largest pores have sizes, in the case of SR, of around 60 to 100 µm (Figure 7a), whereas in SC (Figure 7b) pore sizes range between 60 and 260 µm with most of them ranging from 100 to 170 µm. It can be seen that SR has smaller pores than SC but a larger number of them. The structure of pine which is a softwood is somewhat different with a regular distribution of pore sizes between 30 and 60 µm (Figure 7c). The porous texture of the sawdust remains unchanged after torrefaction, as can be appreciated in Figure 7d. To highlight the smaller pores in SC and SR, images at higher magnification were taken (Figure 8). Again the pores in SC are of a larger size (between 10-25 µm) than those in SR (5-20 µm). The presence of the sawdust with its structure of predominantly large pores can create channels for volatiles to pass through, thereby alleviating the gas pressure inside the pores. In addition it should be remembered that sawdust does not

expand during coking, leaving more intergranular voids for the volatiles to escape out of. Moreover, the formation of fissures also allows the release of volatiles, thereby contributing to a reduction in gas pressure during coal coking. When viewed under the microscope biomass in coke looks very much like the large inerts inherent to cokes [4]. A study of the interfaces between the textural components of cokes shows that those of greatest significance for coke quality are inerts and especially large inerts due to the presence of fissures at their interface [31]. In the case of cokes prepared with biomass more fissured interfaces are likely to appear because some biomass particles are weakly bonded to the coke matrix. Such fissures as well as having an influence on coke quality, may contribute to the release of gas and to a decrease in coking pressure. The interrelationship between fluidity, devolatilization and the low permeability zone during the coal plastic stage together with the porous structure of the semicoke are known to be important factors for the development of coking pressure during coking [14,23]. The differences between T_2 and T_{max} , T_r and T_1 are shown in Table 3. A previous study carried out with single coals clearly demonstrated the temperature range of the low permeability stage and the temperature of the end of the low permeability plateau to be related to coking pressure [14]. Figure 6 shows that the addition of any of the sawdusts tested leads to a decrease in coking pressure and this is reflected in a diminution of the low permeability range which is specially marked by the lower value of T_2 and, in turn, by the smaller T_2-T_1 range. Dangerous coals [14] have a T_2 greater than the temperature of resolidification, as measured by the Gieseler test (T_r), the effect of the addition of sawdust being to reduce the temperature of the end of low permeability zone (Table 2) which is closely associated with a decrease in the coking pressure. The difference between T_2 and T_{max} is also greater in the dangerous coal C2 than in the blends which indicates that the low permeability zone extends over a greater temperature range after the maximum rate of volatiles release has occurred. The difference is due to modifications in T_2 since T_{max} remains almost constant in all the blends between 479 and 481 °C. In the case of the blends containing sawdust the gases that evolve find a

medium that is less restrictive of their movement with a consequent decrease in the coking pressure. In the case of the blends T_{max} is very similar to that derived from the curve of coal decomposition, but the curves show other maxima that correspond to temperatures lower than that of the beginning of the low temperature zone and, as a consequence, these do not cause an increase in pressure (Figures 2 and 3)

3.5 Coke quality

In order to obtain a comprehensive picture of the use of biomass in coking, the effect of the biomass on the quality of the coke was also assessed. The coke reactivity index (CRI) and the strength after reaction (CSR) were used in the present research work to determine the effect of the sawdust on the quality of the coke produced from the blends of coals of sawdust with C1 and C2. As is well known, the lower the CRI and the higher the CSR index is, the better the quality of the coke. There is, therefore, an inverse linear relationship between the CRI and CSR. In the present study a correlation coefficient of $r=0.905$ for C1 and $r=0.841$ for C2 were obtained. For cokes that are destined for use in the blast furnace the CRI indices should be in the range of 20– 30% and the CSR indices, above 60% [32]. The variation of these indices with the amount of sawdust added for C1 and C2 is shown in Figure 9. Although at low levels of addition of around 2 wt% the effect of adding oak sawdust appears to be more deleterious than that of chestnut and pine, at 5 wt% addition the effect is similar. Torrefaction has no effect at all on the CSR index of the coke produced from C1. One of the factors used to explain these differences in coke reactivity is the composition of the ashes. The ash in this type of sawdust is rich in Ca and K that are known to act as catalysts of the carbon gasification reaction and serve therefore to increase the reactivity of the coke [2,7,32,33]. Other authors using charcoals of various sizes have found that the most deleterious effect for coke quality was obtained when the charcoal of the smallest size was used [7,33]. In the present research work the sawdust with the finest particle size distribution was SR (Table 1). The addition of this sawdust produced a lower CSR index with 2 wt% addition but

when the amounts of addition were increased the differences observed between the three sawdusts diminished.

4. Conclusions

Waste sawdusts from pine, chestnut and oak and torrefied pine sawdust were used as additives for mixing with two low volatile coking coals. It was found that all of them modified the devolatilization curve of the coals but no apparent interaction between the biomass and the coal occurred in the blends during thermal decomposition. The log K curve corresponding to the blends shows a narrower zone of low permeability than that of the individual coal which is associated with a decrease in coking pressure.

In addition the large porosity of the sawdust in the blends allowed gases to escape more easily, as a result of which the build-up of pressure was avoided inside reaction mass. Although sawdust clearly has a deleterious effect on coke quality, the addition of sawdust in small amounts (around 2 wt%) helps to reduce coking pressure and maintain an acceptable level of quality.

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Table 1. Main characteristics of the coals and sawdusts.

Sample	C1	C2	SP	SPT	SR	SC
Ash (wt % db)	8.4	10.1	0.3	0.4	0.5	1.5
V.M. (wt % db) ^a	20.9	17.4	84.8	78.5	81.9	76.8
C (wt % db)	84.5	80.6	50.7	56.0	50.2	56.1
H (wt % db)	4.5	4.1	6.1	5.8	5.9	5.2
N (wt % db)	1.9	2.0	0.3	0.4	0.4	0.5
S (wt % db)	0.62	0.61	0.00	0.03	0.02	0.02
O (wt % db)	2.8	2.2	42.5	37.4	44.0	36.7
C/H ^b	1.56	1.64	0.69	0.80	0.71	0.90
C/O ^b	40.1	48.8	1.6	2.0	1.5	2.0
> 3 mm (wt%)	14.5	13.8	0.0	0.0	0.0	1.0
2-3 mm (wt%)	6.7	13.1	3.1	0.0	0.5	4.5
1-2 mm (wt%)	14.2	14.8	17.8	20.3	2.5	24.6
0.5-1 mm (wt%)	18.9	15.7	49.8	48.6	17.8	65.8
< 0.5 mm (wt%)	45.7	43.6	29.3	31.1	79.2	4.1

a: volatile matter. b:atomic ratio.

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455 Table 2. Parameters derived from the permeability tests.

	Tini ^a	T1 ^b	T2 ^b	log K ^c
C2	440	475	525	-12.64
C2+1SC	445	475	515	-12.54
C2+2SC	441	473	510	-12.53
C2+5SC	439	472	517	-12.48
C2+1SR	444	475	509	-11.98
C2+2SR	449	483	512	-12.20
C2+5SR	436	473	505	-12.51
C2+1SP	440	465	514	12.40
C2+2SP	443	474	513	-12.56
C2+5SP	440	475	507	-12.22

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457 ^a: Tini: temperature of the beginning of the reduction of the permeability coefficient.

458 ^b: T1, T2: temperatures of the beginning and end of the low permeability zone.

459 ^c:Log K: minimum value of the logarithm of the permeability coefficient.

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Table 3. Relationship between the parameters derived from permeability test, Gieseler test and thermogravimetric analysis.

	$T2^a - Tr^b$	$T2^a - T_{max}^c$	$T2^a - T1^a$
C2	24	45	50
C2+1SC	15	36	40
C2+2SC	11	30	37
C2+5SC	17	34	41
C2+1SR	12	29	35
C2+2SR	15	32	29
C2+5SR	6	25	31
C2+1SP	18	34	41
C2+2SP	17	32	39
C2+5SP	12	26	32

^a T1 and T2: Temperatures of beginning and end of the low permeability zone.

^bTr: Resolidification temperature from Gieseler test. ^cTmax: Temperature of maximum volatile matter evolution.

Figure 1. Gieseler fluidity loss due to sawdust addition.

Figure 2. TG/DTG curves corresponding to the blends of coal C1 with pine sawdust and torrefied pine sawdust. Inset corresponds to the TG/DTG curves of SP and SPT.

Figure 3. TG/DTG curves corresponding to the blends of coal C2 with the three sawdusts.

Figure 4. Relationship between experimental and calculated coke yields.

Figure 5. Variation of the permeability coefficient with temperature for blends of C2 and the three sawdusts.

Figure 6. Variation of coking pressure with the addition of sawdust.

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566 Figure 7. SEM images of the three sawdusts, a) oak, b) chestnut, c) pine and d) the
567 torrefied pine.

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Figure 8. SEM images of the smaller porous structure of hardwood sawdust a) oak, b) chestnut.

Figure 9. Variation of coke quality (CRI/CSR indices) with sawdust addition for coals C1 and C2