EFEITO DO TAMANHO DE PARTÍCULA E DA UMIDADE SOBRE A DENSIDADE DE MISTURA DE CARVÃO E SEU IMPACTO SOBRE A QUALIDADE DO COQUE *

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Resumo

Uma das propriedades mais importantes no processo de produção do coque é densidade de mistura de carvão. Esta característica pode ser facilmente manipulada por algumas varáveis como umidade e tamanho de partícula que são controladas ou medidas no processo de beneficiamento do carvão em coqueria. A primeira parte deste estudo tem como objetivo entender a variação da densidade por influência da umidade e da granulometria quando se utiliza base úmida e seca. Enquanto a segunda parte mostra como o teor de umidade impacta sobre a qualidade do coque.As investigações mostraram que mudanças sobre a densidade a partir da granulometria requer cuidados, uma vez que pode cair em uma região de alta densidade alcançada por partículas grossas ou em uma região de partículas finas, onde ambas podem comprometer a qualidade do coque. Em relação a umidade, maiores densidades podem ser alcançadas com a secagem ou mesmo com o excesso de umidade na mistura. Entretanto, para um teor de umidade menor como 4%, a diferença de densidade entre a sua base úmida e seca é menor, assim, influenciando na produtividade esperada, bem como permite melhorar parâmetros de qualidade como índice de reatividade do coque (CRI), resistência do coque após reação com CO_2(CSR)e *drum index* (DI).

Palavras-chave:Carvão; Densidade; Umidade; Tamanho de partícula.

EFFECT OF PARTICLE SIZE AND MOISTURE ON COAL BLEND BULK DENSITY AND ITS IMPACT ON COKE QUALITY

Abstract

One important property in the coke manufacturing process is bulk density of coal blend. This feature can be easily manipulated for some variables such as moisture and particle size, which are controlled or measured in the coal beneficiation process in cokemaking. The first part of this study aims to understand the density variation of coal blends by the influence of moisture and particle size when using dry and wet bases.Whereas the second part display as the moisture content impacts on coke quality. The investigations showed that changes on the density from particle size require care, since they can fall in a region of high density achieved by larger particles or in a region with excess coal fines, where both can compromise the coke quality. In relation the moisture, higher density can be reached when drying or even with excess of moisture in coal blend. However, for a lower moisture content as 4%, the difference in the bulk density between wet and dry bases is smaller, thus influencing the expected productivity, as well as permit enhance parameters such as

coke reactivity index (CRI), coke strength after reaction of CO_2 (CSR) and drum index (DI).
Keywords: Coal; Bulk density; Moisture; Particle size.

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1 INTRODUCTION

Metallurgical coke is the main fuel and component in blast furnaces for hot metal production. It is responsible to generate reducing gas, is carbon source, responsible to support the load, in addition plays the key role in maintaining permeability and gas flow through the bed [1]. For a stable performance, coke is required to be of high quality regarding to strength and reactivity, sincewhile it is descending the blast furnace, it suffers chemical and mechanical degradations due Boudouard reaction and mechanical abrasion [2]. Hence, the coke quality depends on coal blending used and the coking process.

Among the coal characterization parameters, the coal charge bulk density is one of the most important properties, which in the case of coke ovens, helps to determine the coal charge to be put into the oven with a specific volume. In addition, the increasing in its value leads to an increasing in coke production, make up for the lack of coal dilation and contribute to an improvement on coke strength[3] that will allow a steady operation of the blast furnace and coke rate reduction.

To increase the density, some coal pre-treatment processes as preheating[4], stamping [4], dry charging [5], briquetting [5], and even, oil addition [6]and mechanical vibration [7]has been commonly employed. Nevertheless, moisture content and coal particle size can have a strong influence on these operations.

In case of moisture influence, Sabadini et al. (2013)[6] and Leeder et al. (2014)[8] reported when the moisture content becomes excessively high as > 11%, the effect of oil addition has no influence on the bulk density increase.

Moisture content in the blend also has impact on productivity. That is when a coal blend of high moisture content is charged into the coke oven that has a certain volume, this implies that for the same density, there will be less coal than expected, reducing productivity. In addition, variations in the moisture content of coal make difficult its crushing capacity, cause adverse effects on the stable operation of coke ovens, leading to an increase on heat consumption and variations on coke quality [8]. Thereby, dryers of coal known as coal moisture control (CMC) were developed by Japanese Industry and applied at the first time in 1983 in order to decrease moisture in coal blends, decrease heat consumption on coke oven and coking time, at the same time improve the coke quality and productivity [9]. However, an overly decline of moisture is responsible for increasing the amount of dust during the transportation and the pulverized coal into the ascension pipes, thus the moisture content must be selected considering these effects [9].

Ellioti (1981)[10] demonstrated in their work, the combined influence of moisture and particle size on bulk density. For the same moisture, bigger particles have higher density. However, the coal particle size and the greater constancy in its distribution become quite critical for the coking process and for the mechanical strength of coke [11].

Silva et al. (2011)[12] justifies the importance of particle size distribution regarding to the petrographic. Because inert materials have higher hardness and resistance to crushing, they are concentrated within higher size range, while reactive macerals, as the softer portion, present an opposite behavior. Due characteristics mentioned previously and to its infusibility, coal crushing becomes a fundamental operation to eliminate the excessive presence of inert that can be responsible for fracture and cracking areas in coke [12].

In contrast, reactive particles of inferior size (< 0.15mm) lose their swelling and fluidity, and their excessive production leads to a decrease in coal charge bulk density. Therefore, the mechanical resistance of coke decreases, once the contact effectiveness between the coal particles decreases [12].

The conventional method to assess the coke quality regarding its reactivity and strength is determinate by Coke Reactivity Index (CRI), Coke Strength after Reaction (CSR) and Drum Index (DI). While DI assess the coke mechanical strength at room temperature, CRI and CSR are combined test that consider the process conditions of the blast furnace. If the coke reacts excessively with the CO_2, it will weaken and will be degraded, leading to the excessive presence of fine particles with consequent efficiency loss and blockage of tuyeres causing operational issues of the blast furnace[13]. Therefore, CRI and CSR parameters are useful to estimate the coke consumption and permeability in the furnace.

In view of this situation, the present article intends to present and understand the effect of moisture content and the particle size variation of coal charge on bulkdensity and its impact on coke quality when considering distinct moisture levels, but for a fixed particle size.

2. MATERIALS AND METHODS

2.1 Determination of coal blend bulk density from moisture and grain size alteration

The coal blend of this work of characteristic showed in Table 1, it was prepared, dried at 105 °C for 2 hours and divided into two grain size fractions by ASTM 7 Mesh sieve. Thus, two base blends were made: one with particle size below 2.83 mm and another with particle size above this range (Figure 1).

Table 1. Analysis of the coal blend used at the first experiment

Coal Type		**ProximateAnalysis**		**Petrographic**	
High Volatile	22	Moisture	6.98	Reactives	69.29
MediumVolatile	54	VolatileMatter	25.72		
Low Volatile	18	Ash	8.07	Reflectance	1.13
Other (Pet coke)	8	Sulphur	0.84		
Rheology					
Maximum Fluidity (Log)	**Softening Temperature**	**MaximumTemperature ofFluidity**	**Solidification Temperature**	**Contraction**	
2.71	403	455	487	-11.54	
Ash Mineral Analysis					
Na_2O	K_2O	Al_2O_3	CaO	MgO	Fe_2O_3
0.58	1.69	26.90	1.95	0.84	7.29
MnO	SiO_2	TiO_2	P_2O_5	ZnO	
0.04	54.81	1.42	0.62	0.02	

New coal blends were composed considering typical ranges for use in top-filling coking plant with particle size 77, 79, 81, 83 and 85% below 2.83mm. The density of each blend was determined from a known fixed volume container and calculated as Bulk density = M/V, where M is coal weight determined and V is volume of the container (see Figure 1).

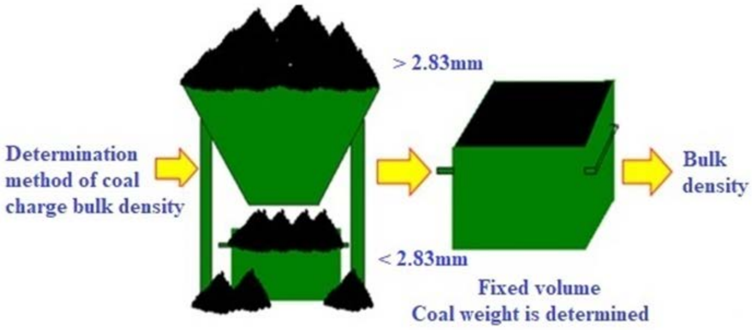


Figure 1. Determination method of coal charge bulk density.

Afterwards, samples were homogenized in a rifle splitter adding water to achieve a moisture content of 4% and new densities were measured. The procedure was repeated, homogenizing and adding water for the following moisture levels: 5, 6, 7, 8, 9, 10, 12, 14 and 16%.

2.2 Coke quality determination with a fixed coal particle size and distinct moisture levels

To investigate the impact of moisture on coke quality regarding reactivity (CRI), strength after reaction with CO_2 (CSR) and drum index (DI), another coal blend it was formulated with the same characteristic as shown in the Table 1, with 85% < 2.83mm particle size and different moisture levels from 4 to 14%.
Subsequently, representative samples of coal were collected for the bulk density measurement as described in 2.1 item. Afterwards, coal blends were charged into the pilot coke oven containing 72 resistors of silicon carbide for heating; dimensions equal 455mm wide x 930mm long x 830mm high; volume 0,350m^3; load capacity of 255kg (dry basis) to a charge density of 750kg/m^3. After 20h process, the coke was quenched by water.
The reactivity and strength test were performed in accordance to ASTM D5341(2014)[14]. An electric furnace with diameter-76.2mm reaction retort for the experiment consisting of three separate heating zones. Initially, coke samples having 19.0mm to 22.4mm size range and initial bulk of 200 ± 2g was charged into the steel retort and heated up to 1100°C under inert atmosphere (N_2, 5 to 10 l/min). After temperature stabilization for 10 min, the atmosphere was changed to carbon dioxide with a flow rate of 5 l/min during 120min. The test was stopped, and retort cooled down to room temperature under N_2. The weight loss percentage of the sample bulk determines CRI value, calculated as CRI = 100*(M1 – M2)/M1, where M1 is the mass of coke before reaction and M2 is the mass of remaining coke after reaction.
The CSR is calculated from remaining mass of the reacted coke sample larger than 9.52mm after its tumbling in a rotatory drum for 30min at 20r.p.m, as CSR = 100*(M3/M2), where M2 is the mass after reaction and M3 is the after tumbling and sieving.
The DI was carried out according to the JIS K2151 standard (2004)[15]. In this test, 10kg of coke samples of particle size > 25mm are tumbling in a drum of 1500 mm intern diameter at 15r.p.m for 10 minutes. At the end, particle size is analyzed from DI^{150}_{15} = 100*(M2/M1), where M1 is initial mass and M2 is the mass retained in 15 mm sieve.

3. RESULTS

3.1 Modification of Bulk Density from Particle Size and Moisture Content

The density results for measurements at all moisture levels and grain size variation on wet basis are presented in Table 2 and on dry basis by discounting of moisture content in Table 3.

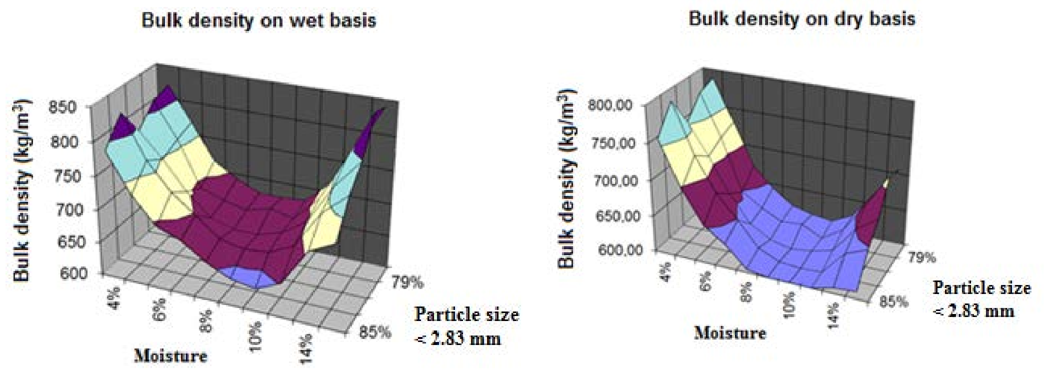
Table 2. Coal blend bulk density for different moisture levels and particle size on wet basis

BULK DENSITY (KG/M^3)										
Particlesize < 2.83mm	Moisture									
	4%	5%	6%	7%	8%	9%	10%	12%	14%	16%
85%	790.74	734.41	694.84	681.65	657.40	640.65	634.59	651.70	706.96	726.21
83%	827.82	765.07	724.78	697.69	669.17	662.04	665.25	683.79	739.05	771.49
81%	784.32	747.96	705.18	672.02	661.68	661.33	672.73	696.98	756.16	798.58
79%	812.13	760.08	690.56	678.08	670.24	680.22	672.38	709.45	775.41	847.78
77%	820.33	768.64	714.45	692.70	677.01	676.66	679.86	712.66	774.34	839.58

Table 3. Coal blend bulk density for different moisture levels and particle size on dry basis

BULK DENSITY (KG/M^3)										
Particlesize < 2.83mm	Moisture									
	4%	5%	6%	7%	8%	9%	10%	12%	14%	16%
85%	759.11	697.69	653.15	633.93	604.81	582.99	571.13	573.50	607.99	610.02
83%	794.70	726.82	681.30	648.56	615.64	602.46	598.72	601.73	635.58	648.05
81%	752.95	710.56	662.87	624.98	608.75	601.81	605.46	613.34	650.30	670.81
79%	779.64	722.08	649.13	630.62	616.62	619.00	605.14	624.32	666.85	712.14
77%	787.52	730.20	671.58	644.21	622.85	615.76	611.88	627.14	665.93	705.25

From these data, graphs were plotted that elucidate the bulk density behavior by grain size and moisture on wet basis and on dry basis (Figure 2).



(a) (b)
Figure 2. Coal blend bulk density for different moisture levels and particle size on (a) wet basis and (b) dry basis.

3.2 Modification of Bulk Density from Moisture Content and its Impact on Coke Quality

The variation of the coal burden bulk density regarding the moisture content and their effects on CRI, CSR and DI parametersare shown in the Figure 3 and Figure 4.

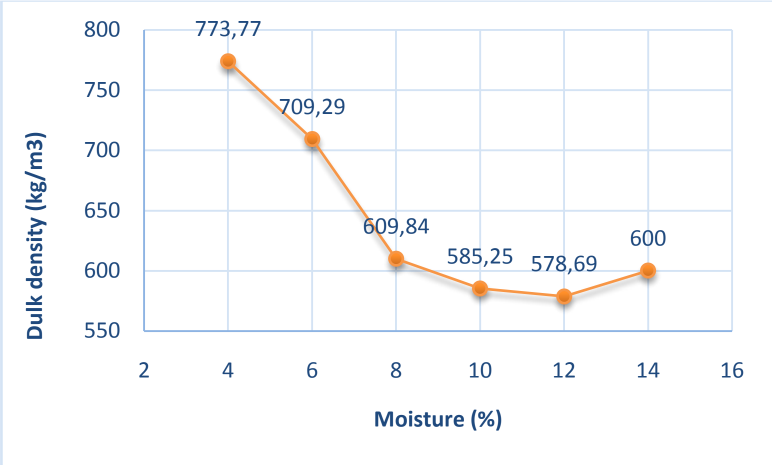


Figure 3. Relationship between bulk density and moisture content.

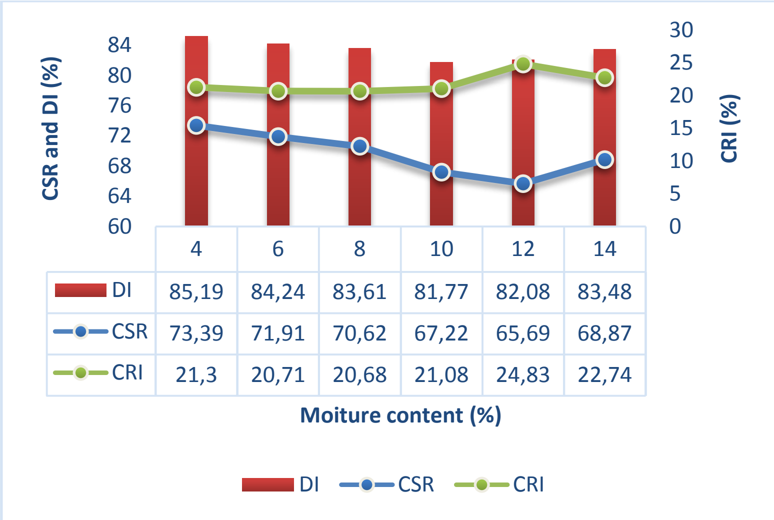


Figure 4. Effect of moisture on CRI, CSR and DI parameters.

4. DISCUSSION

4.1 Behavior of results

The modification of coal charge bulk density under study as dependent of particle size and moisture content is expressed by Equation 1, obtained from a multivariable linear regression of blend bulk density [16,17,18], and with a determination coefficient (R^2) equal to 92.1% [16] was

$$\text{Bulkdensity}=731+39146*\text{Moisture}^2+380*\text{ParticleSize}-9472*\text{Particlesize}*\text{Moisture} \quad (1)$$

Using interacting plots, it can separately realize the moisture and particle size impact on the overlapping of coal blend bulk density for wet basis and on dry basis, as display the Figure 5 and Figure 6.

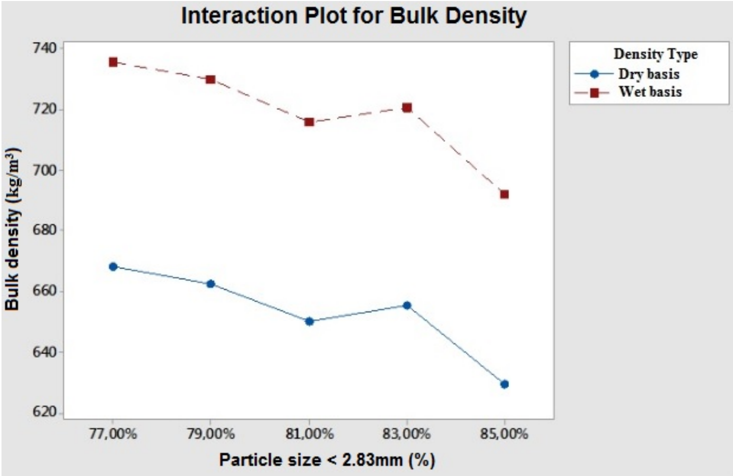


Figure 5. Interaction plot (bulk density/particle size).

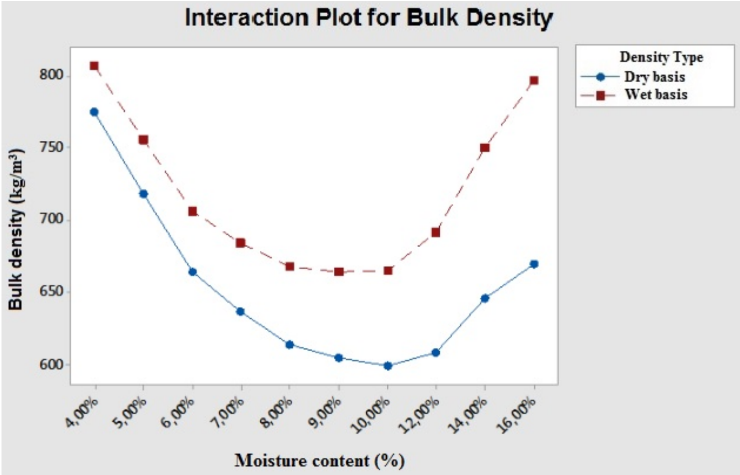


Figure 6. Interaction plot (bulk density/moisture content).

The influence of charge moisture on bulk density as shown in Figure 6 has direct impact on the weight of coal charged in a coke oven, because although the density increases beyond 10%, the difference in the charge bulk density between wet and dry basis is higher, influencing the expected productivity that would be reduced.

4.2 Theories for results obtained

4.2.1 Effect of particle size on charge bulk density

When particles are divided, the total surface area and the number of free space between the particles increase (Figure 7) and the density decrease, since the coal volume increases, justifying the results for an excessive crushing at 81% < 2.83mm. The reason for misunderstanding: the resolution limit of the human eye at a distance of 25 cm is 0.2 mm.

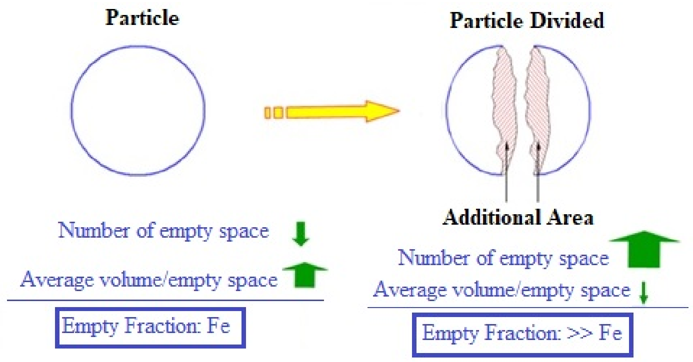


Figure 7. Division effect of a particle on its surface area and void formation.

Thus, the alteration of density due to particle size changes must be careful because the reducing of particle size for finer fractions to 77%, there may be loss of fluidity compromising the coke quality. While for a coarser grain size, it falls into a region where the inert particles will not be fully enveloped by reactive particles and depending on their size, they will serve as cracking points reducing the coke quality too.

4.2.2 Effect of moisture on coal charge bulk density and on coke quality

The effect of the moisture on coal charge bulk density for all cases following a U-shaped curve suffers the action of two effects, the first one will be called substitution and the second, compaction (Figure 8).

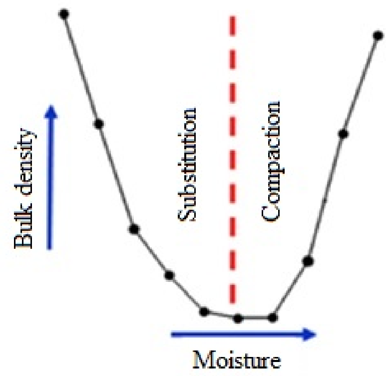


Figure 8. Effect of moisture on coal charge bulk density.

Initially, the bulk density decreases, since coal density is 1.4 g/cm^3 and the water density is 1g/cm^3. Thereby, the substitution of coal by water justifies the result found (Figure 9). The fact of the water enables hydrophobic coal particles to repulse each other, increasing the free space and, consequently, decreasing the density, also can explain the results.

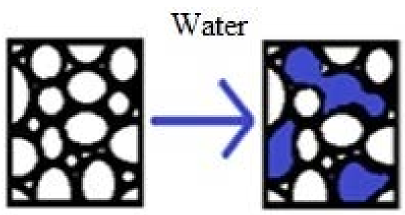


Figure 9. Substitution of coal particles by water.

In contrast, in the second part of the graph the excess moisture causes coal particle agglomeration forming pseudo-particles [19]. Therefore, there is a compaction effect that leads the particle-to-particle distance to decrease and the density to increase again. (Figure 10).

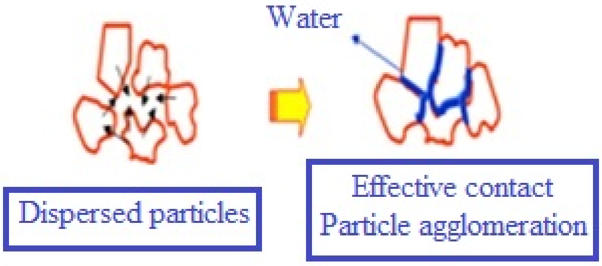


Figure 10. Effect of water addition on particle agglomeration.

The added effects of substitution and compacting lead to the curve shown in Figure 11 that has a valley where the lowest bulk density occurs, which goes up both for high and low moisture levels.

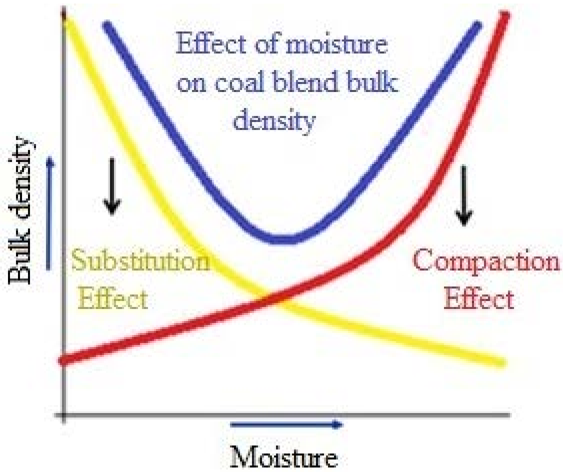


Figure 11. Overlapping of substitution and compaction effects on coal blend bulk density.

In respect to the bulk density gain due to changes in moisture, drying of coals up to 4% is more interesting, because the density difference between its wet and dry bases is lower (see Figure 6), thus the productivity of the coke oven is greatly increased, and the energy consumption is reduced, since there is lower excess moisture to be removed.
As the moisture present in the blend decreases, improvements on CRI, CSR and DI values as display the Figure 7 were found as result of increasing density. The compaction effect explained previously proves the stronger coke formation, once the caking property of coal particles is improved in the coking process as result of effective contact of particles promoted by increasing density.
In addition, the second part of experiments shows, considering the blend with 12% (the lowest point) moisture regarding to the lower moisture blend (4%) a: increase on bulk density of 34% with significant impact on coke batteries productivity; decrease on CRI of 3,53%; increase on CSR of 7,70%; and increase on DI of 3,16%.

5. CONCLUSIONS

Modification on coal blend bulk density for coking processes can be done by changes on particle size, i.e., the coal crushing level, or even drying or humidifying the coal. Adjustment of density in relation to the particle size can fall in a region of high density achieved by larger particles or in a region with excess of coal fines, where both can compromise the coke quality requiring attention. The same way, the drying of coal or even the excess of moisture by an agglomeration process can increase the bulk density. Nevertheless, coal blend with a moisture content as low as 4% can present better benefits during the coking process, on the productivity and on parameters as CRI, CSR and DI. Improvements on the metallurgical coke quality parameters resulting in a reduction of coke rate into the blast furnace, consequently increasing its productivity.

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