Capítulo 2

Thermal and Electrical Conductivity of Coal Powders: A Case Study

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Abstract

In this study, the thermal and electrical conductivity of coal dust extracted from certain coal mines in the metropolitan area of San José de Cúcuta, in the department of Norte de Santander, Colombia, was investigated for the purpose of utilizing them in briquette production. Representative samples of thermal coal from the "La Milenita" and "Salazar" mines were taken and subjected to quartering and air drying. Proximate or physicochemical analyses of the samples were conducted, including sulfur content, swelling index, and calorific value, in accordance with respective ASTM standards. Subsequently, cylindrical samples of coal dust were manufactured with three grain sizes, using water as a binder with a moisture content of 20%. Thermal conductivity was determined as a function of compaction pressure at each mine using the KD2 Pro® equipment. Finally, electrical conductivity was experimentally obtained for the three grain sizes, maintaining a moisture content of 25%.

Keywords:
Coal powder;
Thermal conductivity;
electric conductivity;
KD2;
logistics function.

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Introducction

Colombia is a country with large reserves of high-quality coal, sufficient to supply the domestic and foreign markets (Marín et al., 2024). Most of the reserves are located in the Caribbean and Andean regions, in departments such as Antioquia, Boyacá, Cauca, Cesar, Córdoba, Cundinamarca, Guajira and the Santanderes (South and North). The department of Norte de Santander stands out as one of the main suppliers, being responsible for approximately one-third of these reserves, which are mainly composed of thermal coals. These coals are mainly used in the ceramic production industry, in the manufacture of cement, and in thermoelectric plants (Marín et al., 2024; Rico, 2020). Given its geographic location, a large part of the production is destined for export through the port of Maracaibo in Venezuela (Bautista et al., 2011). On the other hand, in the San José metropolitan area, large quantities of this mineral are used in the production of heat in furnaces, in the generation of steam, and various thermal systems, competing directly with other raw materials such as oil, natural gas and even wood (Valencia & Quiroga, 2022; Ruiz et al., 2012; Bautista-Ruiz et al., 2011).

Coal is a black, combustible, sedimentary metamorphic rock composed of organic and inorganic components of varying abundance and origin (Moore et al., 2022; Nath, 2024). It is mainly composed of carbon (approximately 80%) and other light chemical elements such as hydrogen, oxygen, and nitrogen. Its composition is quite heterogeneous; part of the charcoal, known as charcoal mineral matter, does not come from plant remains, while another part is organic matter derived from plant residues. These residues, through biochemical and geological processes, change their physical and chemical properties (Akinyemi et al., 2021; Gómez et al., 2020).

The inorganic matter present in coal is the result of processes associated with peat accumulation and the evolution of the degree of carbonization (Moore et al., 2022; Thomas, 2020). Anthracite has the highest carbon content, followed by bituminous coal (high, medium, and low volatile), sub-bituminous, lignite, and, finally, peat (Barragan et al., 2021). These components provide geological information on the depositional conditions and formation of coal sequences (Suárez-Ruiz & Crelling, 2008), being essential for the use and application of this fossil fuel (Strambo et al., 2018). One of the most basic ways to characterize coal is by physicochemical analysis, which aims to determine the amount of residual moisture (ASTM D3173), volatile matter (ASTM D3175), ash and fixed carbon (ASTM D3174), as well as sulfur content (ASTM D3172-13), swelling index (ASTM D720-91) and calorific value (ASTM D388-19). This approach constitutes the simplest and most generalized way to characterize coal in the laboratory (Paredes-Celi et al., 2019; Cheng, 2021).

Other properties of interest studied concerning the use of thermal carbon are its thermal and electrical conductivity (Ruiz et al., 2012; Bautista-Ruiz et al., 2011; Bautista et al., 2011). From physical principles, it is known that there are three different mechanisms for heat exchange between a point, a surface, or a hot and a cold body: heat transfer by radiation, convection, or conduction (Eivari et al., 2021). It is well known that metals conduct heat, while wool is a good thermal insulator. To understand the reason for this, it is relevant to relate macroscopic characteristics to microscopic parameters (Ausloos, 2001).

Fourier's law is phenomenological and constitutes a first approximation to the heat conduction model. This law is developed from observed phenomena rather than derived from basic principles. Thermal conductivity can be defined as the intrinsic ability of a material to transmit heat, i.e., it indicates the rate at which energy is transferred through the diffusion process (Forsberg, 2020). For a cylindrical system in which there is only radial heat transfer and no heat generation, it is possible to express the heat conduction law as follows:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) = \rho c_p \frac{\partial T}{\partial t} \quad (1)$$

Where T is the temperature (K), r is the radial distance (m), k is thermal conductivity $(W/m\,K)$, ρ is the density mass density (kg/m^3);, and c_p is the specific heat $(J/kg\,K)$. Considering a steady state with constant thermal conductivity and linear radial heat flow, with boundary conditio $T(r_i) = T_i;\ (r_0) = 0$ and using Fourier's law, it is possible to obtain a solution to the heat equation (Ausloos, 2001; Eivari et al, 2021; Carslaw & Jaeger, 1959). For this purpose, the thermal conductivity is expressed as:

$$k = \frac{q[\ln(t_2)-\ln(t_1)]}{4\pi(T_2-T_1)} \quad (2)$$

Finally, when an electric field $E\,(V/m)$ is displaced in one direction, a current density is produced $J\,(A/m^2)$ due to the charge carriers; in most natural substances, it is observed that the current density is proportional to the intensity of the electric field, the constant of proportionality being known as the electrical conductivity, $\sigma\ (\Omega/m)$ of the material. This is known as Ohm's law (Sibley, 2021). The value of conductivity depends on the characteristics of each material, being very high in excellent metallic conductors and very low in insulators (Serway et al., 2018; Sanches et al., 2023).

When considering a straight wire of area $A\,(m^2)$ and length $L\,(m)$ subjected to a constant potential difference $V(V)$, an electric current is generated $I(A)$ which is related to the potential difference as follows:

$$V = RI \quad (3)$$

Where $R\,(\Omega)$ represents the opposition to the passage of current, also known as electrical resistance. By rewriting equation (3) as a function of the electric field and current density in the wire, an expression can be found that explicitly relates the electrical resistance of the material and its electrical conductivity (Serway et al., 2018; Sanches et al., 2023; Sibley, 2021; Bautista, 2011), being this:

$$\sigma = \frac{L}{RA} \tag{4}$$

In this work we report the results of the characterization of the mechanical, thermal, and electrical properties of coal from two mines belonging to the department of Norte de Santander, considering coal grains of three different grain sizes, compacted at different pressures. The results of this research will be relevant for rethinking how to reuse the reuse of coal dust generated during the extraction, transportation, and use of coal in the industry, which is usually considered waste. This strategy focuses on the production of compact briquettes to reduce the environmental impact footprint.

Methodology, materials and methods

Different samples of thermal coal were taken from the "La Milenita" and "Salazar" mines, which were supplied by the San Carlos coal company, located in Cúcuta. Once the samples were obtained, they were subjected to quartering and air drying, then crushed with a mechanical mill to obtain the coal powder, which was classified into three-grain sizes using sieves: #100 (149 µm), #50 (297 µm) and #30 (595 µm), according to A.S.T.M E1195, E-323, D-410 standards.

To perform the proximate and technological analyses, a total of 50 g of coal from each mine was quartered and crushed with a passing sieve #60 (250µm) according to ASTM D2234 and ASTM D7430-08 standards. Then the physicochemical analysis was carried out to determine its chemical and physical composition, as well as the technological test to calculate the amount of sulfur, swelling, and calorific value, following the aforementioned standards. The results are reported in Table 1.

Thermal conductivity

To measure the thermal conductivity, the thermal charcoal was dried for 24 h at 40°C in an air circulation oven. Subsequently, cylindrical samples of coal powder were manufactured with 20% moisture (Ruiz et al., 2012; Bautista-Ruiz et al., 2012), as shown in Figure 1. Using the KD2 Pro® Thermal Properties Analyzer (Decagon-Devices, 2011), the thermal conductivity was experimentally determined for each mine, as illustrated in Figure 2. The experimental design involved introducing a constant amount of the wet coal powder mixture into high-pressure cylindrical molds. Using a hydraulic press, force was applied to a plunger to compact the coal. Once the sample was compacted, its conductivity was measured at room temperature. Several cylinders were prepared by varying the compaction pressure. The results for the different granulometries can be seen in Figures 4, 5 and 6.

Figure 1. Thermal carbon powder compaction pressure system. Ceramic Materials Research Center CIMAC. Francisco de Paula Santander University.

Source: own elaboration

Figure 2. Measurement of the thermal conductivity of carbon powder by means of the KD2 PRO® equipment. Ceramic Materials Research Center CIMAC. Francisco de Paula Santander University.

Source: own elaboration

The KD2 PRO® calculates thermal conductivity, resistivity and diffusivity values by monitoring the heat dissipation of an on-line heat source, given a known voltage. When an electrically heated long probe is inserted into the sample and a heat pulse is sent, the temperature rises from an initial temperature to a specific distance, from the probe, is:

$$T - T_0 = \left(\frac{q}{4\pi k}\right) E_i \left(\frac{-r^2}{4Dt}\right) \quad (5)$$

where is the heat produced per unit length per unit time (W/m), D is the thermal diffusivity (m^2/s) and E_i is the exponential integral function

$$-E_i(-a) = -\gamma - \ln\left(\frac{r^2}{4Dt}\right) + \frac{r^2}{4Dt} - \left(\frac{r^2}{8Dt}\right)^2 + \cdots \quad (6)$$

Being $a = r^2/4Dt$ and the Euler constant (Ruiz et al., 2012; Decagon-Devices, 2011; Fontana et al., 2001). If sufficiently large time intervals are taken, it is possible to neglect the higher-order terms presented in Eq. (6). Thus, the temperature variation obtained after suspending the heat source is:

$$T - T_0 = \frac{q}{4\pi k}\left[\ln(t) - \gamma - \ln\left(\frac{r^2}{4D}\right)\right] \quad (7)$$

Equation (7) presents a linear behavior between the change in temperature and the logarithm of time. In this case, the KD2 Pro® equipment can obtain the thermal conductivity of the sample according to equation (2). For the analysis of the results, a logistic growth function with a saturation limit is used, described as:

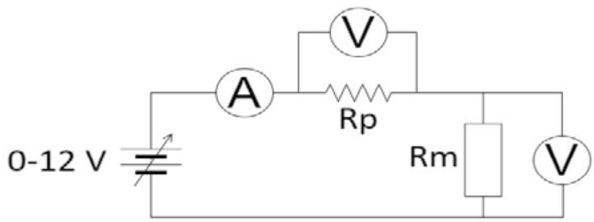
$$y = \frac{A_1 - A_2}{1 - \left(\frac{x}{x_0}\right)^p} + A_2 \quad (8)$$

Which is a solution to the Nelder model, in which the parameter A_1 represent the value of the thermal property (thermal conductivity) of the sample without compaction pressure, A_2 is the value of the property with large compaction pressure (maximum saturation value), x_0 is the point at which the change in curvature occurs, and p the growth rate (Wu et al., 2020; Jukić & Scitovski, 1996).

Electrical conductivity

For the measurement of electrical conductivity, the setup shown in Figure 3 was recreated with the carbon samples. In this case, data were taken for the three-grain sizes of each mine, varying the voltage between 0 and 12 V DC, in a mixture of powder and distilled water with a moisture content of 15% and 25%.

Figure 3. Equivalent circuit in the performance of electrical conductivity tests.



Source: own elaboration

In the circuit shown in Figure 3, the value of R_P represents the test resistance, used to determine the value of the electric current flowing through the series circuit. On the other hand, R_m corresponds to the value of the electrical resistance of the sample of thermal carbon mixed with water at 25% humidity, deposited in an insulating container of known dimensions (Bautista et al., 2011). From the measurements made, the respective graph of V vs I was generated for each mine and its corresponding particle sizes, as shown in Figure 10 and Figure 11. Finally, the respective data analysis was carried out according to the theory.

Result and analysis

Table 1 presents the physicochemical analyses of the "La Milenita" and "Salazar" mines. As can be seen, these mines have two very similar types of coal. The swelling index indicates that being low, the presence of thermal coal deposits is confirmed in both cases. In addition, based on the amount of fixed carbon and volatile matter, it is determined that this mineral was classified as Bituminous type, characterized by being dense, black and hard, containing high A-B volatiles according to Barragan et al., 2021.

Table 1. Physicochemical and technological analyses obtained in the characterization of the coal.

Analysis	La Milenita mine (%)	Salazar mine (%)
Humidity	0.56	0.69
Ash	4.91	5.77
Volatile Matter	41.39	38.55
Fixed Carbon	53.14	54.99
Sulfur	0.69	0.72
Calorific Value	7722 Cal/g	7282 Cal/g
Swelling	2	4

Source: own elaboration

Results thermal conductivity

Figures 4 to 9 present the results of thermal conductivity under compaction pressure for each mine. It is evident that both mines show similar thermal conductivity values, even for different grain sizes. Using the logistic function (Eq. 8), it is observed that the first conductivity value (P=0) is low compared to the rest of the values, with a value near to $\kappa = 0.165\ W/mK$. From the second measurement onwards ($P = 250\ psi$), this physical parameter increases notably, reaching values close to $\kappa = 0.182\ W/mK$.

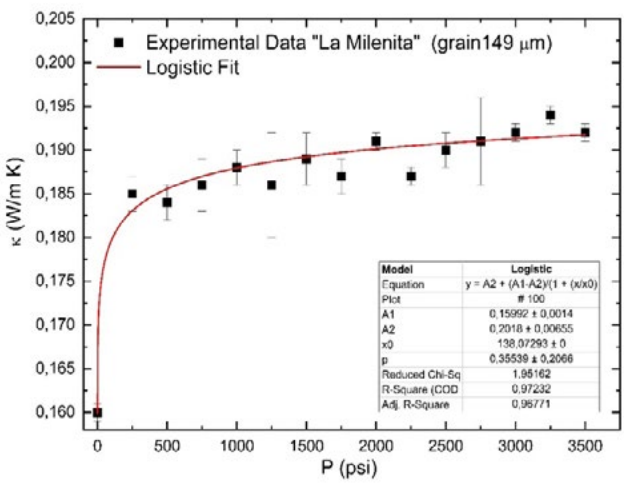
It can be assumed that the coal powder, not being under pressure, is more dispersed and may contain small regions of air that would hinder effective heat conduction. When pressure is applied to the sample, the charcoal is compacted, bringing the grains closer together and improving the heat transfer mechanism. It is also observed that, for subsequent measurements, the thermal conductivity continues to increase, but the change is not as significant as in the first measurement. Thus, for elevated pressures, the thermal conductivity remains almost constant and even, in some cases, tends to decrease slightly.

For the “La Milenita” mine, it is observed that the thermal conductivity shows a more favorable behavior for the #100 sieve, where a lower compaction pressure (250-1000 psi) is required for its application in the production of briquettes. However, the other grain sizes also show a consistently good approximation in the results, without the need to exceed 2500 psi of pressure.

As for the “Salazar” mine, it is observed that the thermal conductivity obtained for the #100 sieve is slightly better than for the #50 sieve, but requires a higher compaction pressure (1000-2000 psi) compared to the sample from the other mine. For the #30 sieve of this mine, it is observed that it takes longer to reach an approximately constant conductivity, reaching pressure values up to 3500 psi.

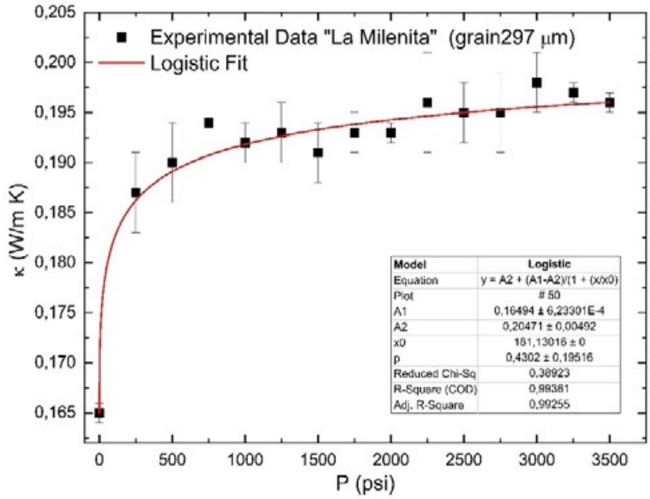
On the other hand, experimentally it was observed that, for high-pressure values, the sample begins to dry out because the pressure expels the water, which partially contributes to thermal conduction. This causes the thermal conductivity values to be almost constant or slightly decreasing compared to the values recorded for the pressures reported above. In addition, the grains are so close together that the change in density or volume of the sample is practically negligible.

Figure 4. Thermal conductivity vs. compaction pressure at La Milenita mine for a #100 sieve tests.



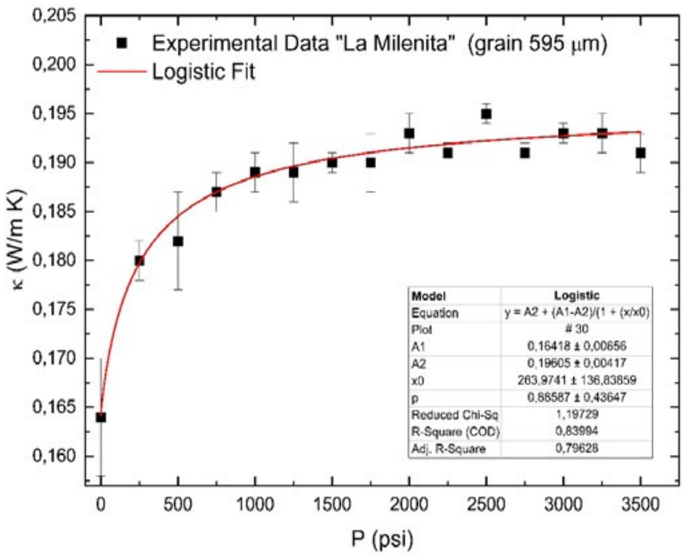
Source: own elaboration

Figure 5. Thermal conductivity vs. compaction pressure at La Milenita mine for a #50 sieve.



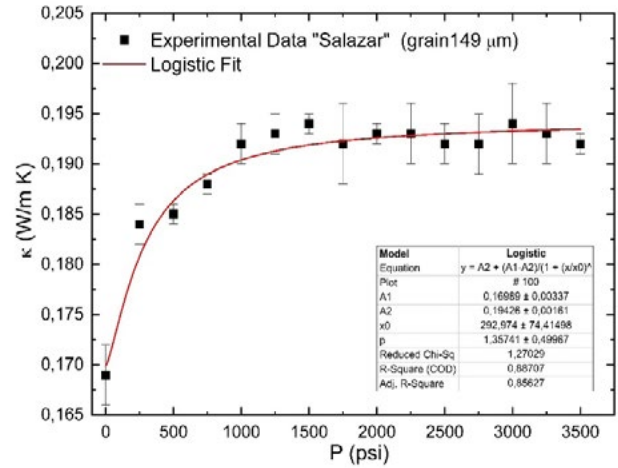
Source: own elaboration:

Figure 6. Thermal conductivity vs. compaction pressure at La Milenita mine for a #30 sieve.



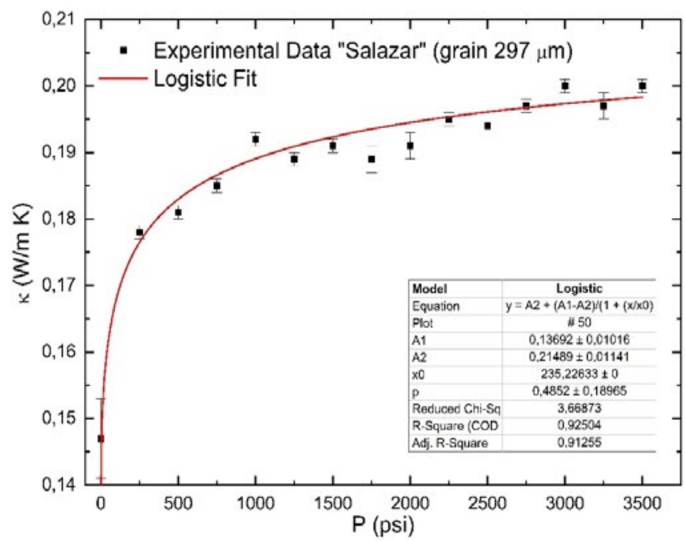
Source: own elaboration

Figure 7. Thermal conductivity vs. compaction pressure of Salazar mine for a #100 sieve.



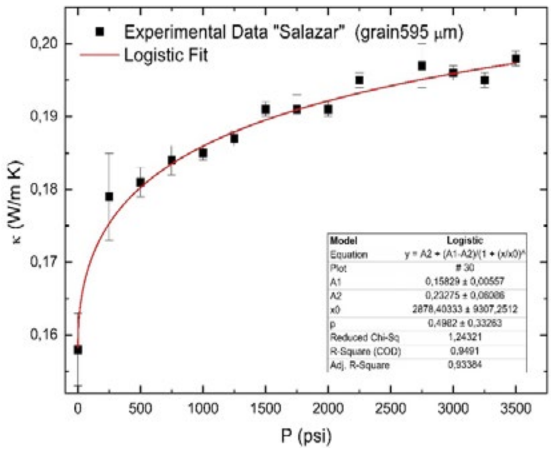
Source: own elaboration

Figure 8. Thermal conductivity vs. compaction pressure of Salazar mine for a #50 sieve.



Source: own elaboration

Figure 9. Thermal conductivity vs. compaction pressure of Salazar mine for a #30 sieve.



Source: own elaboration

Results electrical conductivity

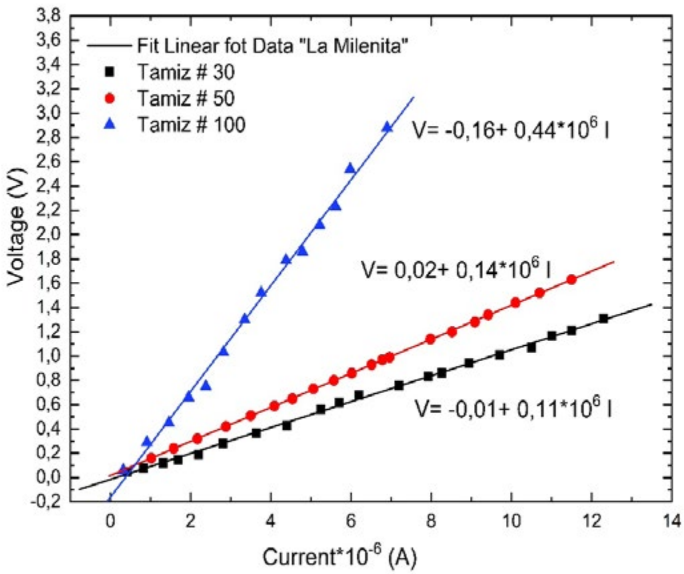
For the electrical conductivity test, a test resistor was used with a value of was used to control the current in the circuit. Figures 10 and 11 show the Ohm's law results for the "Salazar" and "La Milenita" mines. Table 2 shows the electrical conductivity parameters for each grain size.

Table 2. Electrical conductivity of coal for different grain sizes.

Electrical Conductivity			
Mine	**Sieve #30**	**Sieve #50**	**Sieve #100**
Salazar	8.06	5.01	2.11
La milenita	1.62	1.22	0.40

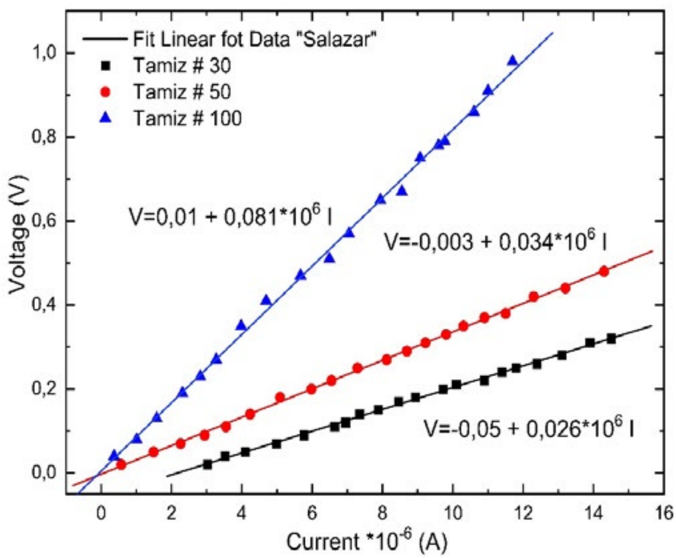
Source: own elaboration

Figure 10. Ohm's Law at different grain sizes for the "Salazar" mine.



Source: own elaboration

Figure 11. Ohm's Law at different grain sizes for "La Milenita" mine.



Source: own elaboration

Figures 10 and 11 show a linear behavior typical of ohmic materials. In both mine samples, an increasing trend of the electrical resistance exerted by the coal is noted as the grain size becomes smaller. This is reflected in Table 2, where the measured values of electrical conductivity are found. The "Salazar" mine presents a better behavior in terms of electrical conductivity, with a maximum of $\sigma = 8.06 * 10^{-5}\ \Omega/cm$ in comparison with the "La Milenita" mine, which has a maximum of $\sigma = 1.6 * 10^{-5}\ \Omega/cm$ being the first mine the best electrical conductor.

According to Table 1, "Salazar" has a higher amount of ash, which is usually indicative of the presence of conductive materials that benefit the transport of electric current. On the other hand, as the grain size decreases, the surface area increases, which means that the water added to the sample has to be distributed to a greater extent. This results in a smaller amount of surface area being occupied for a constant concentration, creating an insulating barrier. Therefore, better electrical conductivity is observed for sieves with a larger grain size.

Conclusion

Coal samples from the Salazar and La Milenita mines were characterized, obtaining thermal conductivity as a function of compaction pressure and electrical conductivity.

It is observed that the Salazar mine presents better electrical conductivity compared to the La Milenita mine. Likewise, the grain size that presented the best electrical conductivity is 595 µm (sieve #30).

The thermal conductivity of the La Milenita mine does not present significant changes in thermal conductivity when changing the grain size, while in the Salazar mine it is observed that its thermal conductivity increases slightly for larger grain sizes. However, being so small would reflect that in the practice of briquette manufacturing it is not impactful.

This study provides a basis for the reuse of coal dust arising from the extraction, transportation and processing of thermal coal from the Norte de Santander region and will contribute to the creation of briquettes that could be used in the most efficient way possible, thus generating a positive impact on environmental problems and sustainable development.

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Conductividad térmica y eléctrica de polvos de carbón: un caso de estudio
Condutividade térmica e elétrica de pós de carvão: um estudo de caso

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Resumen

En este estudio se investigó la conductividad térmica y eléctrica de polvos de carbón extraídos de algunos yacimientos carboníferos del área metropolitana de San José de Cúcuta, en el departamento de Norte de Santander, Colombia, con el propósito de utilizarlos en la producción de briquetas. Se tomaron muestras representativas de carbón térmico de las minas "La Milenita" y "Salazar", las cuales fueron sometidas a cuarteo y secado al aire libre. Se llevaron a cabo análisis próximos o fisicoquímicos de las muestras, incluyendo la cantidad de azufre, el índice de hinchamiento y el poder calorífico, conforme a las respectivas normas ASTM. Posteriormente, se fabricaron muestras cilíndricas de polvos de carbón con tres tamaños de grano, utilizando agua como aglutinante con una humedad del 20%. Se determinó la conductividad térmica en función de la presión de compactación en cada mina mediante el equipo KD2 Pro®. Finalmente, se obtuvo experimentalmente la conductividad eléctrica en los tres tamaños de grano, manteniendo una humedad del 25%.
Palabras clave: Polvo de carbón; conductividad térmica; conductividad eléctrica; KD2; función logística.

Resumo

Neste estudo, investigou-se a condutividade térmica e elétrica de pós de carvão extraídos de algumas jazidas carboníferas da área metropolitana de San José de Cúcuta, no departamento de Norte de Santander, Colômbia, com o propósito de utilizá-los na produção de briquetes. Foram coletadas amostras representativas de carvão térmico das minas «La Milenita» e «Salazar», as quais foram submetidas a quarteamento e secagem ao ar livre. Foram realizadas análises próximas ou fisicoquímicas das amostras, incluindo a quantidade de enxofre, o índice de inchamento e o poder calorífico, conforme as respectivas normas ASTM. Posteriormente, foram fabricadas amostras cilíndricas de pós de carvão com três tamanhos de grão, utilizando água como aglutinante com uma umidade de 20%. Determinou-se a condutividade térmica em função da pressão de compactação em cada mina utilizando o equipamento KD2 Pro®. Por fim, a condutividade elétrica foi determinada experimentalmente nos três tamanhos de grão, mantendo uma umidade de 25%.

Palavras-chave: Pó de carvão; Condutividade térmica; condutividade elétrica; KD2; função logística.