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A Study on Electrical Resistivity Characteristics of Pakistani Coal Char for Earth Grounding System

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Abstract

In this study, we aim to investigate the electrical conductivity and physiochemical properties of the selected coal samples for their application in earth grounding systems. Three different ranked coals namely Thar brown lignite (BL), Chamalang bituminous coal (BC), and semi-anthracite Dera Adam Khail (SC) coals were selected and their respective chars were prepared at 450 °C. These samples were then subjected to the ground resistivity potential test using the universal earth grounding tester. Through experiments, it was found that BL coal has the least reactivity value and the best conducting properties for electric current, followed by the SC and BC in descending order. It has been suggested that high moisture content and dissolved salts may act like an electrolytic medium for current passage in BL which is the reason for low resistivity value. The presence of low conductivity minerals in a small percentage having relatively higher mass could be the reason for higher resistivity value in coal samples. Moreover, compared to raw coals, prepared char samples exhibited an improvement in electric current conductivity and lowered the resistivity values for all the ranks of selected samples.

Keywords: Char, Electrical resistivity, Physiochemical properties, Earth grounding.

1. Introduction:

Globally ongoing expeditious growth in population has led to a rapid surge in urbanization, and socioeconomic and industrial sector development [1,2]. According to the United Nations (UN) watch source, the increase in human population growth is expected to be 10% by the end of 2030 [3]. Energy is considered to be one of the fastest-growing sectors amongst the top economic developmental growth indicators [4,5]. The UN SDGs-12 deals with the responsible production and consumption of energy which covers almost all the important consumable production areas of human life [6]. Sustainable power production and consumption is one of the problematic areas for the developing world [4,7]. Current or electricity is a form of energy that can hurt human lives when precautionary measures are not taken properly [8]. An electrical safety system is considered to be the fundamental requirement for every electric power generation, supply, and equipment manufacturing system [9]. The International Electro-technical Commission (IEC), founded in (1906), has established various technical and standard regulations for electric generation,

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supply, and electronics equipment manufacturing systems [10].

Worldwide sky lightning is one of the major natural disastrous challenges for electric power supplies and distribution systems [8,11]. Several catastrophic events are happening every year around the globe due to natural lightning events. As a result, loss of human lives and other infrastructure damage occur. Earth grounding of the electric current is one of the most important techniques that have been in practice since old times. Since the beginning of the earth grounding technique, several systems and standard methods have been developed [12]. However, IEC technical recommendations standardized the grounding systems in line with the TC (81-99) and SC-64. For safe electric supplies, IEC recommended the ground electric current flow resistance value should not exceed 10 (ohm) [11].

During electric power generation, unwanted electrical discharges such as; overvoltage or lightning, may occur. These discharges are denoted as failures and may pose an electric shock hazard to personnel passing through the site and compromise the veracity and proper functionality of the installed equipment in the facility [13]. These operational failures can also reduce the energy efficiency of power generation and transmission units which leads to wastefulness in energy consumption, instigating economic damage to stakeholders and consumers [14]. Therefore, it is imperative to have a proper grounding system to manage and avoid electrical hazards. Factors that could affect the earth's impedance are soil properties, grounding rod geometry, the number of rods, and the existing climate of the region. The most important parameter for designing an earth grounding system is the grounding resistance. This parameter is related to the electrical conductivity of the soil and the total length of the buried metal rods and railings. Lower electrical conductivity soils, such as sandy soils, require longer-length buried metal structures and vice versa to achieve safe ground resistance levels [15]. Furthermore, soil electrical conductivity is greatly affected by the amount of water confined in it; since increasing its moisture implies a decrease in its resistivity [14]. Taking this point into consideration, the earth grounding material must be capable of moisture retention.

While increasing the mesh and grounding electrode length is not physically more viable due to territorial restraints, another common methodology is to treat the soil chemically with specific materials that can act as ground resistance reduction agents which increase the electrical conductivity of the ground and achieve adequate grounding resistance without applying a physical method of reduction. These materials can be either organic or inorganic in nature. Generally, an organic earth-grounding material is derived from natural sources while an inorganic earth-grounding material comprises a chemical that is most often industrial waste [16]. Different researchers have employed diverse materials as an alternative to earth resistance-reducing agents such as; 'Bentonite', 'Palm kernel oil cake', 'Coconut coir peat, planting soil and paddy dust mixture', 'Bentonite, pig dung, domestic salt, and charcoal amalgam', 'Steel industry residue composed of iron oxide (Fe_2O_3)', 'Sodium chloride, sodium thiosulphate, magnesium chloride, cuprum sulfate, and ammonium chloride', and 'fly ash' [17-23].

Pakistan is renowned for its fossil coal deposits, which are estimated to contain nearly 186.6 billion tons of coal reserves. This accounts for almost 73% of the country's total known fossil fuel assets [24,25]. The majority of the country's coal deposits, approximately 97%, are ranked from lignite to sub-bituminous in nature, while the remaining 3% are anthracite and high-ranked. However, the quality of coal deposits found in the country is generally considered low-grade due to the presence of high ash-forming mineral matter and water content in certain cases, such as Thar coal. Table 1 presents a detailed chemical analysis of some major coal deposits [26]. In addition to this, nearly 249.5 billion tons of unrecoverable coal deposits exist worldwide that are distributed around different regions, with almost 50% of the total coal reserves being low-rank lignite to low-rank sub-bituminous and the rest of the reserves as the bituminous and anthracite in nature [24-26].

Globally emerging de-carbonization policy given the IPCC framework emphasizes the use of non-fossil renewable resources to minimize the CO_2 emission risk under the 2 °C scenario [27,28]. Under such circumstances, renewable energy resources are rapidly replacing the conventional coal combustion energy production processes [4]. Hence, the alternate use of coals in petrochemicals and other related industries should be encouraged for environment-friendly utilization of the indigenous natural fossil fuel resource [29].

In literature, several studies have been published related to the various physical, thermal, and chemical characterization techniques to consider the suitability of the coals for energy conversion processes [30-32]. Some researchers' work on the non-conventional electrical characterization properties has been published in the literature [33,34]. Authors have investigated the conductivity behavior of the coal deposit seem and its allied rocks to examine the self-heating spontaneous fire-catching propensity [35]. In another study, the electrical and thermal conductivity behavior of the 'barapukuria' coal was analyzed [36]. Most of the published work on the electrical properties of coal has been limited to the solid coal core rock that measures either parallel or perpendicular to the seam bedding plane [34,37]. The current work is designed to explore the electrical conductivity behavior of the powdered coal samples loaded inside the earth borehole for earth grounding potential application. Chemically, coal varied in composition with rank and geological history [38]. Three different ranks lignite, bituminous and semi-anthracite coals have been selected for the current grounding electrical resistivity investigation. Apart from that, the effect of thermal treatment like pyrolysis has been also used to investigate the electrical resistivity potential while also determining the suitability of the coal samples for earth grounding systems as per IEC standards

Table 1: Coal reserves of Pakistan and their average proximate analyses

Regions	Coal Fields	Coal Reserves (Million Tons)	Average Proximate Analysis (%)				
			Total Moisture	Volatile Matter	Fixed Carbon	Ash	Total Sulfur
Balochistan	Duki	50	3.5-11.5	32-50	28-42	5-38	4-6
	Sor Range Degari	50	3.9-18.9	20.7-37.5	41-50.8	4.9-17.2	0.6-5.5
	Chamalang	06	1.1-12.9	24.9-43.5	19.4-47.1	9.1-36.5	3-8.5
	Khost Sharig	76	1.7-11.2	9.3-45.3	25.5-43.8	9.3-34	3.5-9.55
Punjab	Makarwal	22	2.8-6	31.5-48.1	34.9-44.9	6.4-30.8	2.8-6.3
	Salt Range	213	3.2-10.8	21.5-38.8	25.7-44.8	12.3-44.2	2.6-10.7
Sindh	Lakhra	1328	9.7-38.1	18.3-38.6	9.8-38.2	4.3-49	1.2-14.8
	Sonda - Thatta	3700	22.6-48	16.1-36.9	8.9-31.6	2.7-52	0.2-15
	Sonda Jherruk	1823	9-39.5	20-44.2	15-58.8	5-39	0.4-7.7
	Indus East	1777	9-39.5	20-44.2	15-58.8	5-39	0.4-7.7
	Thar Coal	175505	29.6-55.5	23.1-36.6	14.2-34	2.9-11.5	0.4-2.9
KPK	Hangu	82	0.2-2.5	16.2-33.4	21.8-49.8	5.3-43.3	1.5-9.5
	Cherat	9	0.1-7.1	14-31.2	37-76.9	6.1-39	2.3-5.4
	Dara Adam Khail	3.75	2-6	5-7	75-84	16-22	1.5-3

2. Materials & Methods:

2.1 Sample Collection and Preparation:

Brown lignite coal (BL), Bituminous coal (BC), and Semi-anthracite coal (SC) samples used in this study were sourced from Thar, Chamalang, and Dara-Adam Khel coal fields respectively. Thar, Chamalang, and Dara- Adam Khel fields are located in the Sindh, Balochistan, and Khyber

Pakhtun Khawa provinces of Pakistan respectively. All the coal samples were collected and prepared following the ASTM guidelines. The selected coal samples were subjected to the hammer mill to crush and reduce the nominal top particle size below 4 mm. The crushed coal fractions were then pulverized using the double plate roller disk mill and then sieved through 60 mesh size sieves to obtain uniform fractions of samples. All the prepared samples were then preserved separately in sealed polythene bags for further investigation such as; physiochemical characterization in the form of detailed proximate, structural, pyrolysis, and resistivity analyses.

2.2 Coal Char Preparation Through Pyrolysis:

Pyrolysis of the selected coal samples was performed in a fixed-bed tube furnace reactor. The selected coal samples were placed inside the tube reactor using a specially designed ceramic boat. The nitrogen purge gas stream was maintained at a rate of 3 liters/min for all test runs. The temperature was maintained at 450 °C for 20 minutes to ensure the complete removal of all forms of moisture and light-weight volatile hydrocarbons. At the end of every pyrolysis test run, the reactor was cooled down to ambient conditions while the nitrogen purge was continuously maintained inside the reactor tube to avoid any risk of sample combustion. After the cooling process, the resulting char was taken out for each test run and preserved in sealed bags for further investigation.

2.3 Characterization Analysis:

Coal samples' chemical characterization (i.e. proximate analysis) was performed under the ASTM standard guidelines specified for each test involved in the proximate analysis. The heating value of the fuel in the form of gross calorific value (GCV) was found by using an automatic bomb calorimeter (Parr 6200, USA). The total carbon and sulfur contents in the samples were found by using an automatic carbon sulfur analyzer (LECO, USA). Structural analysis of the coal samples was carried out through the non-destructive functional group identification using Fourier Transform Infrared (FTIR) spectroscopic analysis technique.

2.4 Ground Electric Current Resistivity Measurement:

Electrical resistivity analysis of the selected raw coals and coal char samples was evaluated using the procedure of the related ASTM standard. Resistivity is the indirect measurement of the current flow through a specific medium. In this study electrical resistivity value ‘ ' was calculated from Equation 1, given as:

$$\rho = \mathrm{R}\left(\frac{\mathrm{A}}{\mathrm{L}}\right) \qquad (1)$$

'R' represents the resistance value, and 'L' and 'A' are the coal bed thickness and cross-sectional area of the testing probe respectively. A resistivity test was performed on a plain, earth-ground area using a 6-inch ground hole. Resistivity tests were performed using powdered raw coal and coal char samples. The raw coal and coal char samples were loaded into the standard specification cylindrical ground hole and the current was maintained through the digital earth tester probe. The current passage flow rate was measured using a digital earth resistivity meter UNI-T UT521.

3. Results & Discussions:

3.1 Characterization Analysis Results:

Results obtained from chemical characterization analysis were evaluated for Thar brown lignite (BL), Bituminous Chamalang (BC), and Semi-anthracite Dara Adam Khail (SC) for both raw coal and char samples and they are presented in Table 2. It is obvious from Table 2 that moving from lignite to semi-anthracite ranked coals, chemical constituents varied. The total moisture content percentage on air-dried coal samples was found to be the highest for lignite followed by the bituminous and semi-anthracite coals respectively [38]. This has been explained as the low-rank coals like BL usually have the highest percentage of oxygenated functional groups in the form of a variety of water-forming -OH functional groups with the associated higher conductivity and low-temperature thermal stability characteristic properties [32]. In general, with the coal rank progression under accelerating temperature and pressure, loss of loosely attached oxygenated functional groups occurred with the more structurally tightened R-O-R, R-O-Ar bridge structural arrangement appearing within the molecular coal structure [31,39].

In several investigations, it has been discussed that almost all types of moisture for all ranks of coal are lost at temperatures nearly 110° C. And almost all the loosely bounded oxygenated -OH functional groups are released at temperatures below 250° C [40]. Hence no traces of moisture were detected for fixed bed pyrolyzed BL, BC, and SC char samples, as found in Table 1. Volatile matter content in the coal is correlated to the light gaseous volatiles that might emit as the consequence of the thermally less resistant aliphatic and side chain functional groups dissociation [41,42]. For both raw and charcoal samples volatile matter found the arrangement of BL > BC > SC. The descending volatile matter content with the increasing ranks of coal may have close relevance with structural maturity.

The percentage of ashes in the coal samples varied as BL< BC< SC. BC was found to have the highest percentage of ash content that may have different thermal and electrical conductivity properties [33], [35,43,44]. Mineral matter constituents present in coal ashes are generally inorganic in nature that could also vary in composition and percentage masses with the geological changing deposit's history and conditions [45,46]. In the literature, no direct relevance has been reported between ash mass percentages with coal ranks. The mass percentage share in the pyrolyzed coal char samples was higher as compared to raw coal samples due to the potential loss of moisture and volatile matter species [47]. The total and fixed carbon content found in the raw and pyrolyzed sample depicted the rank dependency [48,49]. Moving from lower BL to higher SC rank coals, both total and fixed carbon content in the pyrolyzed and raw coal samples showed increased percentage values. This could be narrated to the coal molecular structural aromaticity that increases with the coal rank progression, as found in the present case [50].

The gross calorific value for coal samples has also shown the same characteristic pattern as predicted for the carbon content values (Table 2). Generally non-combustible content in the coal samples like moisture and inorganic ash forming mineral matter suppresses the heating content value [31]. Whereas, the carbon content shows a positive contribution to heating value enhancement in coal samples. The gross heating values (GCV) were found to be in the arrangement BL< BC< SC for raw and pyrolyzed coal samples respectively. The total sulfur content followed in the coal samples has variable percentages that also show no direct relation with coal ranks. For both raw and pyrolyzed samples, BC has the highest mass percentage share of sulfur amongst the studied samples. Sulfur normally found in coals is in organic, inorganic, and sulfate forms [51]. The specific type of sulfur's chemical nature and its abundance may have different physiochemical and thermal conversion behavior [52]. Generally higher sulfur percentage in coals is highly undesired, owing to the corrosive chemical nature.

3.2 FTIR Analysis:

Fourier transform infrared spectroscopy analysis of the raw and pyrolyzed samples was performed in the wavenumber range of 500 to 3500 cm^{-1} and the results are shown in Figure 1. The non-destructive FTIR spectroscopy is reported to have the efficacy in determination of functional groups in solid samples like coal [53]. In the published literature, several authors have studied the relative percentage abundance of different functional groups that helps us to understand the macromolecular structural rings [54]. The relative absorbance peaks in the wave region 4000 to 3300 cm^{-1}, 3000 to 2700 cm^{-1}, and 2000 to 1000 cm^{-1} confirm the existence of a variety of water-forming OH, straight chain aliphatic, and aromatic attached functional groups respectively in all the samples used in this study [32].

The description of the possible functional groups' existence at a particular wavenumber has been described in Table 3. From Table 3, it can be noticed that the BL sample depicted the multiple peak intensities for -OH groups that could be present as part of different forms of water and other loosely bounded phenolic functional groups. In the aliphatic region, peak intensities have gradually reduced with the rank progression. Whereas, multiple higher intensity peaks could be observed as the sequence progresses from lower to higher rank coals. When compared between the raw coal samples and their respective pyrolyzed coal char samples, improvisation in the structural maturity may be identified as the relative increase in aromatic functional group peak intensity with subsequent reduction in the aliphatic and hydroxyl groups [55].

Table 2: Chemical characterization analysis of the raw and pyrolyzed coal samples

Samples Type	Moisture %	Volatile matter %	Fixed carbon %	Ash %	Total carbon %	Total Sulfur %	GCV (Cal g^{-1})
Raw BL	16.9	42.10	28.6	8.2	62.5	2.2	4759.32
Raw BC	7.76	38.86	40.78	13.11	71.5	4.3	6038.96
Raw SC	4.23	14.08	72.31	10.19	82.7	3.6	6785.31
BL Char	-	19.71	48.05	9.84	71.4	1.4	5820.46
BC Char	-	28.43	55.89	15.68	83.6	3.2	6493.16
SC Char	-	5.74	82.88	12.68	86.7	2.7	6993.33

Table 3: FTIR Assignments Identified for the Different Functional Groups

Wavenumber (cm^{-1})	**Peak Assignments**
3447	- OH Stretch
2928	Aliphatic Straight Chain
2848	Symmetric - CH_2 and - CH_3 Stretch in Aliphatics
1747	C=O, - COOH Stretch
1636	C=O Stretch in Aromatics (Carbonyl Groups)
1490	C=C Stretch in Aromatics
1412	Asymmetric - CH_2 and - CH_3 Vibrations in Aliphatics
1165	C - O Stretch in Phenols, Ethers
1018	Stretch in Minerals

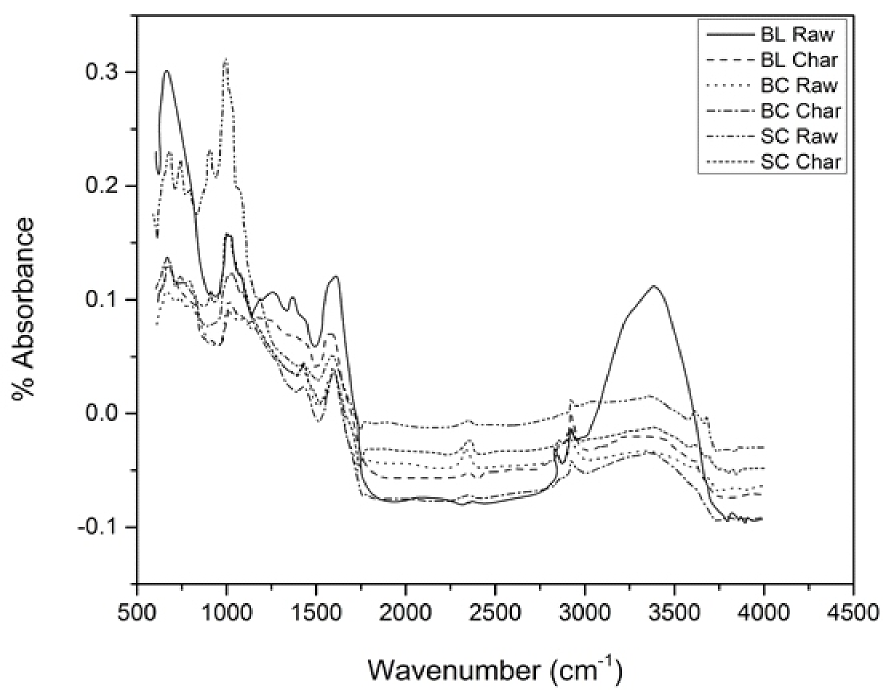

Figure 1: FTIR analysis of the raw and pyrolyzed char-prepared coals.

Table 4: Units for magnetic properties

Sample Types	Resistivity Values ρ (Ω.m)
Soil	50.1
Raw BL	0.59
BL Char	0.26
Raw BC	114.12
BC Char	13.16
Raw SC	8.25
SC Char	1.04

3.3. Earth Grounding Resistivity Measurement Results:

The measured resistivity analysis results have been summarized in Table 4. From Table 4, the lowest resistivity values were found to be of the BL raw and coal char. Whereas, BC coal has the highest resistivity values for raw and coal char samples. SC coal resistivity values were found to be in between the BL and BC raw and pyrolyzed coal samples. Amongst the raw coal samples, the lower resistivity value for BL could be regarded as having a higher moisture content [36]. It is a generally admissible fact that moisture in coal samples may act like an electrolyte conducting source for current passage. Hence it may reduce the electrical resistivity values through lower resistance values [36,56]. The argument is supported by the literature-reported work [34].

Apart from the moisture value, mineral matter in the coal samples may have an accelerating impact on the resistivity value. BL placed the lowest in an ash-forming mineral matter which could also contribute to the lowered resistivity value [33]. In the case of the BC sample highest resistivity value can be associated with the lower moisture content, complex structural nature, and higher mass percentage share of electrically resistant mineral matter as predicted by the highest ash percentage from Table 2 [33,36,43]. In the case of AC, resistivity value may relate to the compact aromatic structural arrangement [43]. D. Tillman explained that with the coal rank maturity, aromatic cluster ring size changes. Several fused aromatic rings have the highest concentration in anthracite rank coals due to which a more complex rigid graphite-like structure came into existence [56]. When compared to raw coals, pyrolysis lowered the resistivity values as predicted for all the ranks of coal samples. This is in good agreement with the literature-supported arguments [47]. B. Feng et. al. reported that thermal treatment like pyrolysis may alter the structural arrangement by creating the molecular chain ordering within the coal macromolecular structure [57]. The thermal treatment variation effect on the percentage decrease in electrical resistivity values has been shown in Figure 2.

The scope of this study can be further extended to the internal structural changes that occur during the thermal treatment of coal, such as pyrolysis, which can affect its electrical conductivity. Additionally, future avenues may include the blending of powdered coal and coal char with other prospective materials to investigate their effects on earth grounding resistance.

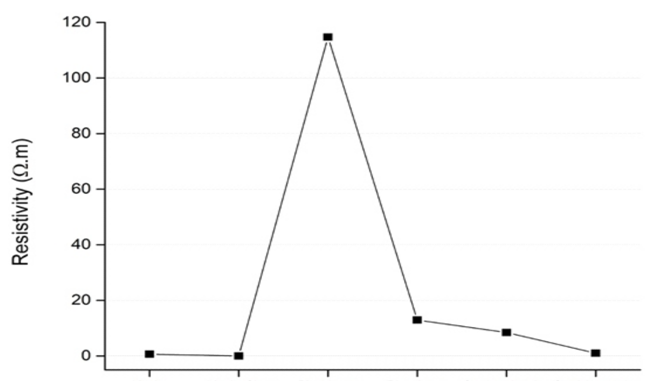

Figure 2: Variation effect in earth grounding resistivity value for raw & charcoal sample

4. Conclusions:

The scope of the work presented in this study was to determine the physiochemical and electrical resistivity characteristics for different ranks of coal in raw and char forms to exploit the potential for earth grounding applications. Raw and fixed bed pyrolyzed coal samples were trialed for resistivity test using the earth grounding test. It has been concluded that low-rank Thar brown lignite (BL) coal showed good conducting properties with low resistivity potential amongst all the other higher-ranked bituminous Chamalang (BC) and Semi-Anthracite, Dera Adam Khal (SC) coals. BC coal sample showed the least conducting properties, whereas the SC coal sample's resistivity value was close to that of the BL coal. Pyrolyzed coal char samples offered better conducting properties compared to raw coal samples. Hence, it has been concluded that lignite and semi-anthracite coals could be used as cost-effective alternatives to expensive graphite and some other low-resistivity materials for earth grounding applications.

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