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Electrical resistivity of *Acacia* and *Eucalyptus* wood chars

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Electrical resistivity of *Acacia* and *Eucalyptus* wood chars, produced under different carbonization conditions, were measured using a two-probe technique. The results have shown that the final carbonization temperature is the most important factor because of its strong influence on the wood char resistivity. The electrical resistivity of these wood chars decreased drastically on increasing the carbonization temperature up to about 800 °C followed by a slight decrease with further rise of temperature up to 1200 °C. The wood species and increase in soaking time at carbonization temperatures of 800 and 1000 °C also influenced the char resistivity. It is hoped that the electrical resistivity values of wood chars can be used to determine their preparation temperature and to have a better control of the operation of electrosmelting furnaces using wood char as reductant.

1. Introduction

As a result of excessive fossil fuel consumption by power and metallurgical industries, the CO_2 concentration in the atmosphere, during the last 100 years or so, has increased from about 295 p.p.m. by volume in 1860 to the current level of 345 p.p.m. [1, 2], which may be disastrous for the human survival in the coming few decades. In this regard, any effort to substitute fossil fuel by some renewable source of energy would be a timely and positive step towards energy and environmental crises facing the world. In the present context of tropical climate, vast waste-land availability and cheap human resources, biomasses show promise for developing nations.

The electrical resistivity test can serve as a controlling device to the operation of an electric reduction furnace where the electrical resistivity of the raw material plays an important role in designing the power system as well as power consumption of the process [3]. The reductant used in electrothermal smelting of iron ores has to perform a dual function of being the reducing agent and also the resistance for generation of heat within the furnace [4]. During smelting, a bed of reductant is formed under the electrode and its resistance to the passage of current, in fact, generates most of the heat produced in the furnace. Prakash and Marincek [3], during their study on electrical conductivity of coke and iron ore mixtures at high temperature, have indicated that this test can be used to predict the coking temperature of coals and the suitability of the resultant coke for metallurgical purposes. The electrical resistivity of the reductant is, therefore, an important parameter by which to assess its suitability for electrothermal smelting of iron ores and also to prepare the most suitable burden for other ironmaking processes.

A search of the literature shows numerous studies on electrical resistivity/conductivity of coals, cokes, pitches, graphite, some synthesized and pyrolytic carbons, etc., but to our knowledge, very few studies have been made on changes in electrical resistivity of wood char with heat-treatment temperature and other carbonizing parameters. Dobmaier (see [3]) and others [5–10] studied the changes taking place during the conversion of coal to char/coke. According to their observations, the electrical resistivity is markedly affected by the physical and chemical changes occurring during the process of carbonization. Emmerich *et al.* [11], while studying the room-temperature electrical resistivity of heat-treated (up to 2200 °C) endocarp of *Babassu* nut, indicated that the electronic conduction process occurs in the structure with the involvement of microcrystallites and micropores. Moreover, they also observed that the temperature dependence of the electrical resistivity of heat-treated *Babassu* nut was similar to that obtained by Hernandez *et al.* [10] in heat-treated coals and *Eucalyptus* wood chars.

In view of the paucity of published data on electrical resistivity of biomass chars and growing interest of metallurgists towards their utilization for ironmaking, it was considered desirable to determine electrical resistivity values of wood chars. The present work was conducted to measure the electrical resistivity of chars derived from *Acacia* and *Eucalyptus* wood (suitable for energy plantations under Indian conditions) under different carbonization conditions.

2. Experimental procedure

2.1. Preparation of wood chars

In the present investigation, preparation of wood chars was carried out by carbonizing wood samples

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under two different heating-cooling cycles, namely slow and rapid. Fig. 1 shows the typical time-temperature profile for slow and rapid carbonization processes adopted in the present investigation.

While carbonizing according to the slow schedule, the air-dried wood pieces (15 mm cube), placed in a stainless steel retort, were kept inside the muffle furnace and heated slowly from room temperature to predetermined carbonization temperatures of 400, 600, 800, 1000 and 1200 °C at the rate of approximately 4 °C min^{-1}. The samples were soaked at these final carbonization temperatures for a period of 1 h and then allowed to cool in the furnace. To examine the influence of soak time on resultant wood char resistivity, the wood samples were carbonized slowly at temperatures of 800 and 1000 °C with the soak period varied from 1–5 h.

In carbonization following the rapid schedule, the air-dried wood pieces (15 mm cube) were placed in the stainless steel retort, which was then inserted into the muffle furnace maintained at the required carbonization temperatures of 400, 600, 800 and 1050 °C, respectively. The retort was kept in the furnace for 1 h and then it was taken out and cooled in air.

2.2. Electrical resistivity measurement

Electrical resistivity was measured by using a two-probe technique, as done by other workers for materials such as graphite [12], pitch [13], polyethylene–carbon fibre composites [14], amorphous Se_{100-x}–Sb_x [15], endocarp of *Babassu* nut [11], etc. The sample (approximately cubic in shape, size 0.76–0.78 cm) was placed between two parallel and circular copper discs of 11 mm diameter and 3 mm thickness held in a locally fabricated spring-loaded conductivity cell (made of copper). The contact resistance was eliminated by placing silver foils between the sample and the disc's surfaces. Prior to resistivity measurements, samples were dried in an air oven for 2 h at 110–120 °C.

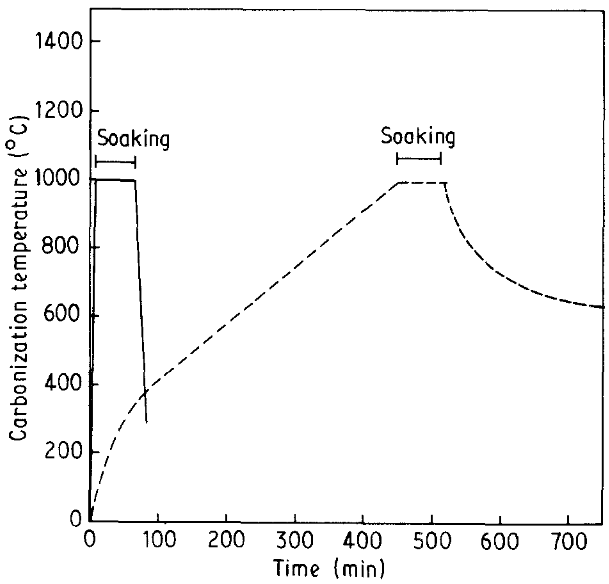

Figure 1 Typical time–temperature profile for (– – –) slow and (——) rapid carbonization.

The d.c. electrical resistivity was determined by measuring the resistance using a digital multimeter (pp 9006 Philips, India, (range $\geqslant 10\,\text{M}\Omega$)) and further verified by a potentiometer (range $\geqslant 500\,\Omega$)). The dimensions of the samples were measured with the help of a slide callipers. After determining the cross-sectional area, A, length, L, and resistance, R, of the samples, the resistivity values were calculated from the formula [16]

$$\text{Resistivity} = \frac{R\,A}{L}\,\Omega\text{cm} \qquad (1)$$

3. Results and discussion

The results obtained are listed in Tables I and II and shown graphically in Figs 2–4. The observations made during this study (i.e. the effects of various carbonization conditions and wood species on the resulting wood char electrical resistivity) are discussed below.

3.1. Carbonization temperature

The room-temperature electrical resistivity of *Acacia* and *Eucalyptus* wood chars, produced under slow and rapid heating–cooling cycles, is plotted on a log scale as a function of their carbonization temperature in Fig. 2. As shown in this figure, the chars made from these wood species showed a decrease in their electrical resistivities with increase in their preparation (carbonization) temperature, the decrease being more intense up to 800 °C after which it became small, i.e. the effect of charring temperature on electrical resistivity of the resulting wood char diminishes as the wood sample is carbonized at higher temperatures. This dependence of electrical resistivity of wood char on its preparation temperature is consistent with the results of Emmerich *et al.* [11] working with heat-treated endocarp of *Babassu* nut and Hernandez *et al.* [10] working with heat-treated coals and *Eucalyptus* charcoal. In addition, the present result is also in good agreement with earlier reports on various other materials such as coals [8, 17], pitch [13], carbon films [18] and polymer carbons [19].

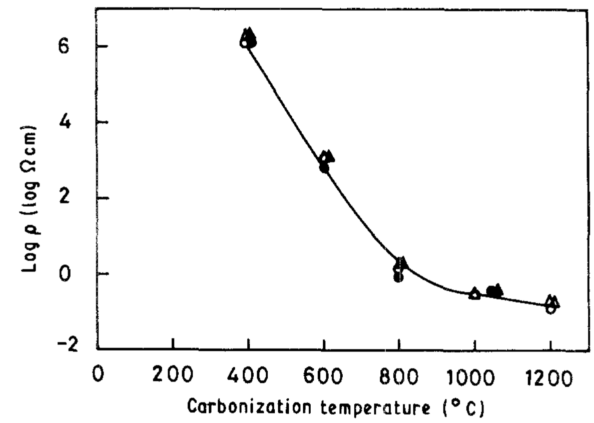

Figure 2 Effect of carbonization temperature on wood char electrical resistivity of (○, ●) *Eucalyptus* and (△, ▲) *Acacia*, after 1 h soak, and (○, △) slow, or (●, ▲) rapid carbonization.

TABLE I Electrical resistivity of *Acacia* and *Eucalyptus* wood chars produced under different carbonization conditions

Sample	Carbonization condition			Electrical resistivity (Ωcm, dry basis)
	Programme	Temperature (°C)	Soaking time (h)	
Acacia wood chars	Slow	400	1	1620×10^3
	Slow	600	1	1485
	Slow	800	1	1.69
	Slow	1000	1	0.30
	Slow	1200	1	0.18
	Rapid	400	1	1800×10^3
	Rapid	600	1	1601
	Rapid	800	1	0.95
	Rapid	1050	1	0.36
Eucalyptus wood chars	Slow	400	1	1300×10^3
	Slow	600	1	1118
	Slow	800	1	1.24
	Slow	1000	1	0.30
	Slow	1200	1	0.14
	Rapid	400	1	1190×10^3
	Rapid	600	1	620
	Rapid	800	1	0.97
	Rapid	1050	1	0.38

TABLE II Electrical resistivity of *Acacia* and *Eucalyptus* wood chars prepared under slow carbonization by soaking the wood samples for varying periods of time at temperatures of 800 and 1000 °C

Sample	Carbonization condition			Electrical resistivity (Ωcm, dry basis)
	Programme	Temperature (°C)	Soaking time (h)	
Acacia wood chars	Slow	800	1	1.69
	Slow	800	2	0.66
	Slow	800	3	0.41
	Slow	800	5	0.46
	Slow	1000	1	0.30
	Slow	1000	2	0.22
	Slow	1000	3	0.18
	Slow	1000	5	Not determined
Eucalyptus wood chars	Slow	800	1	1.24
	Slow	800	2	0.55
	Slow	800	3	0.44
	Slow	800	5	0.46
	Slow	1000	1	0.30
	Slow	1000	2	0.17
	Slow	1000	3	0.18
	Slow	1000	5	0.21

The variation in room-temperature electrical resistivity of *Acacia* and *Eucalyptus* wood chars with increase of heat-treatment (carbonization) temperature appears to be due to the removal of insulating volatile matters and breakage of C–H bonds. During carbonization at temperatures up to about 800 °C, the loss of volatiles predominates and results in an increase in both the fixed (carbon microcrystallites) and total carbon contents of the resulting wood chars [20]. However, at higher carbonization temperatures (i.e. above 800 °C), the volatile release becomes small and, as a result, the breakage of cross-links (non-conducting component) and microcrystallite alignment, become significant. Secondly, during carbonization of wood, hydrogen is released as a result of the breakage of the C–H bond and is completely devolatilized from the sample at a carbonization temperature of about 800 °C [20]. The breakage of the C–H bond, which results in the formation of free valence electrons, also appears to contribute to the electrical conductivity of resulting wood chars. The evidence is given in Fig. 3, where the log of electrical resistivity has been plotted as a function of H/C ratio. The decrease in resistivity with decrease of H/C ratio is very marked in this figure. Thirdly, it has been found that, with the increase of carbonization temperature, both the true specific gravity and the C/H ratio of the wood chars produced, increase. This means that the extent of aromatization of wood char matrix increases with increasing carbonization temperature, as suggested by Neely [19]. This aromatization of the wood char matrix leads to a decrease in its resistivity, due to the fact that the aromatic nuclei have a low energy gap and high conductivity [8].

It thus seems fairly clear that the abrupt decrease in resistivity with increasing carbonization temperature up to about 800 °C (Fig. 2) is mainly associated with the loss of volatiles (i.e. an increase in the mass of the carbon microcrystallites), the breakage of the C–H bond (i.e. loss of hydrogen), and aromatization of the wood char matrix. Later in the carbonization temperature range 800–1200 °C, the resistivity decreases slowly, due to the diminishing enrichment of the wood char matrix with carbon microcrystallites.

3.2. Carbonization programme

In the present investigation, the change of carbonization programme (i.e. heating–cooling cycle) appears to have no noticeable effect on the electrical resistivity of the resulting wood chars, i.e. the effect being random could not be distinguished.

3.3. Soaking time

The variation in room-temperature electrical resistivity of *Acacia* and *Eucalyptus* wood chars, produced under slow carbonization at temperatures of 800 and 1000 °C with soaking time (range 1–5 h) is shown in Fig. 4. It can be observed that, unlike carbonization temperatures, the soaking time has little effect on electrical resistivity of wood chars produced. The chars made from both the wood species at 800 °C showed a sharp decrease in their electrical resistivities with increasing soaking time up to 2 h, followed by a further decrease of smaller magnitude at 3 h, and then

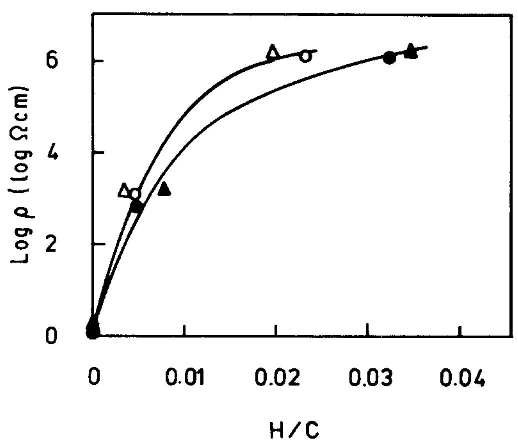

Figure 3 Relation between electrical resistivity and H/C ratio of (△, ▲) *Acacia* and (○, ●) *Eucalyptus* wood chars after (○, △) slow, or (●, ▲) rapid carbonization.

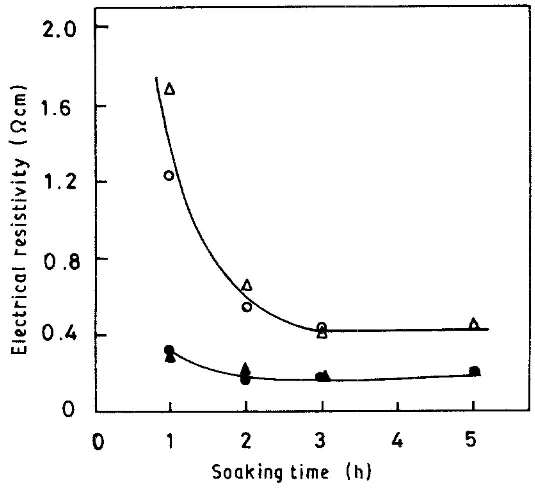

Figure 4 Effect of soaking time on wood char electrical resistivity for (○, ●) *Eucalyptus* and (△, ▲) *Acacia* after slow carbonization at (○, △) 800 °C or (●, ▲) 1000 °C.

remained approximately constant. For wood chars made at 1000 °C, the resistivity decreased slightly with increasing soaking time up to 2 h, after which the change was not distinguishable. In fact, the change in electrical resistivity above the 2 h soak period was so small that it could not be measured by the technique used here.

The decrease in the electrical resistivity of 800 °C slowly carbonized *Acacia* and *Eucalyptus* wood samples with increasing soaking time up to 3 h is closely related to their increased carbon content (i.e. the mass of the carbon microcrystallites) and aromatization of the matrix, as shown previously [20]. Holding the *Acacia* and *Eucalyptus* wood samples isothermally at a carbonization (slow) temperature of 1000 °C yielded chars, the carbon content of which increased with increasing soaking time up to 2 h and then remained nearly constant up to the range studied (i.e. 5 h) [20]. This shows that the variation in electrical resistivity of 1000 °C slowly carbonized *Acacia* and *Eucalyptus* wood chars with soaking time is undoubtedly a strong function of their carbon content. Such dependence of the electrical resistivity of wood char on its carbon content is consistent with the results of Pope and Gregg [21], Ouchi [8] and Duba [9]. All these researchers were concerned with the study of electrical conductivity of coals and coal chars. The improvement in structural ordering occurring as a consequence of prolonged heating at these temperatures [20] is also expected to contribute to the electrical conductivity, as referred to by Fischbach [22].

3.4. Wood species

It is evident from the present study that the effect of wood species on electrical resistivity of the resulting chars is marked only up to the carbonization temperature of about 800 °C, while above this temperature, the wood species has a negligible effect. At lower carbonization temperatures up to about 800 °C, *Acacia* wood yielded chars having an electrical resistivity higher than that of the *Eucalyptus* wood chars prepared at the same carbonization temperatures. At higher carbonization temperatures (i.e. above 800 °C), the chars obtained from both wood species showed approximately similar electrical resistivities. The results cited above can be seen very clearly in Tables I and II.

The principal chemical constituents of wood are cellulose (thermally less stable) and lignin (thermally more stable). The values of electrical resistivity and energy gap for cellulose (up to the temperature of its complete decomposition) are higher than those of lignin [8]. The ratio of cellulose to the more dense lignin is higher in *Acacia* wood compared to *Eucalyptus* wood [20]. This indicates that the higher resistivities of low-temperature *Acacia* wood chars (made up to the carbonization temperatures of 800 °C, 1 h soak), in comparison to similarly prepared *Eucalyptus* wood chars (Tables I and II), are most probably because of its relatively higher cellulose (which has an electrical insulating effect) and lower lignin (which has high conductivity and low energy gap) contents. On heating, cellulose decomposes first and appears to volatilize completely up to the carbonization temperature of 800 °C (2 h soak) or 1000 °C (1 h soak), and as a result of this, only the macromolecules (i.e. lignin char, aromatic compounds, etc.) remain in the resulting wood char. Above the temperature of 800 °C (1 h soak), the chars produced from both the wood species have approximately the same resistivity value at a given carbonization temperature (Tables I and II), clearly because of the complete volatilization or decomposition of cellulose

4. Conclusions

The carbonization conditions affected the electrical resistivity of wood chars in a significant manner. The main findings derived from the present experimental results are as follows:

1. The chars produced from both the wood species (*Acacia* and *Eucalyptus*) showed an abrupt decrease in their electrical resistivity value with increasing carbonization temperature up to about 800 °C, followed by a slight decrease with further rise of temperature up to 1200 °C.

2. Electrical resistivity values of wood chars decreased with increasing soaking time up to about 3 h, but thereafter they remained practically constant up to 5 h soaking.

3. The electrical resistivity test could be used to monitor the wood char quality.

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