

Thermal Conductivity of Carbon Pellets Prepared from Oil Palm Bunches

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ABSTRAK

Sifat-sifat semulajadi, kos yang rendah dan terdapat dalam kuantiti yang banyak sebagai bahan buangan adalah antara faktor-faktor yang menjadikan tandan kosong kelapa sawit (TKKS) berpotensi besar untuk digunakan sebagai bahan pemula bagi menghasilkan elektrod-elektrod karbon pepejal dan komponen-komponen elektrik. Salah satu sifat yang penting bagi produk berkenaan adalah kekonduksian terma. Kekonduksian terma pelet-pelet karbon yang disediakan daripada serabut tandan kosong kelapa sawit diukur pada suhu 150°C menggunakan teknik dinamik. Nilai yang diperolehi adalah 1.38 Wm⁻¹ K⁻¹. Nilai ini adalah 2 hingga 5 kali lebih kecil daripada nilai yang diramalkan dalam kajian ini, nilai untuk karbon yang disediakan daripada selulos, nilai untuk karbon komersil yang diukur dalam kajian ini dan nilai yang dinyatakan oleh pengeluar produk karbon glasi. Perbezaan ini adalah disebabkan oleh mikrostruktur karbon-TKKS yang lebih porous berbanding dengan produk-produk karbon yang lain.

ABSTRACT

Factors such as its natural properties, low cost and availability in large quantities as a waste product may give oil palm empty fruit bunches (EFB) a great potential for use as a precursor for producing solid carbon electrodes and electrical components. One of the important properties of this product is its thermal conductivity. The thermal conductivity of carbon pellets prepared from fibres of oil palm empty fruit bunches was measured at the temperature of 150°C using the dynamic technique. The value obtained was 1.38 Wm⁻¹ K⁻¹, which is 2-5 times lower than the value predicted in this work, the value for carbon prepared from cellulose, the value for commercial carbon measured in this work and the value quoted by manufacturer for glassy carbon product. This difference is due to the microstructure of the EFB-carbon which is more porous than the other carbon products.

Keywords: oil palm empty fruit bunches, carbon pellets, commercial carbon, dynamic technique, thermal conductivity

INTRODUCTION

Oil palm empty fruit bunches (EFB) is a waste material produced in large quantities by palm oil mills. The estimated annual total of EFB produced in Malaysia is about two millions tonnes dry weight (Sha'ari *et al.* 1991). At

present the material is utilized as mulch and, after burning, as fertilizer. Studies to widen its utilization, such as for making tiles, pulp and paper (Mohamad 1993a) and for making solid carbon products (Mohamad 1993b, 1993c, 1994, 1995; Mohamad and Mohd Pauzi 1995; Mohamad *et al.* 1995) have been carried out.

Imports of solid carbon products to Malaysia for the period 1989-1993 were valued at about RM100 million (Mohamad 1993a). Solid carbon products are widely used as electrical components, for example as electrical heating elements, electrodes (spectroscopic, electrothermic, electrolytic and welding), electrical carbon brushes, and lighting and arch carbons. For these types of applications, the thermal conductivity of the solid carbon plays a very important role because one of its working mechanisms involves the heat or energy transfer. Studies of this quantity have therefore been done by many researchers, for example, by Davidson and Losty (1963), Misho and Bakr (1990), Kastelein *et al.* (1992) and Klemens and Pedraja (1994). Davidson and Losty (1963), for example, measured the thermal conductivity of glassy carbon from cellulose at 25°C and 1500°C and the values obtained were 4.2 Wm⁻¹ K⁻¹ and 16.7 Wm⁻¹ K⁻¹ respectively.

This paper presents the results of thermal conductivity measurements conducted at the temperature of 150°C on carbon pellets from fibres of oil palm empty fruit bunches (carbon-EFB) and commercial carbon (carbon-A) using the dynamic technique proposed by Lee (1982). The data obtained were compared with the predicted values and the values for the commercial glassy carbon B and C, and several other carbon samples available in the literature.

THEORY

Consider a system where a sample is sandwiched between two metal blocks of known thermal capacity. Suppose that block A acts as a heat source maintained at a constant temperature and the heat will travel across the sample S to reach block B. For an unsteady-state conduction or dynamic methods, the thermal conductivity of the samples derived from the one-dimensional heat equation is given by Lee (1982) as

$$k = \frac{L}{a} \left[\left(\frac{\tau}{C} \right) \left\{ 1 + \frac{T_c - T_\infty}{T_\infty - T_0} \right\} \right]^{-1} \quad (1)$$

where L is the sample thickness, a (>>L) is the cross-sectional area of the sample (through which the heat travels from block A to B), τ is the time taken so that $T_c - T = \frac{1}{2}(T_c - T_0)$, T_c is the temperature of block B, T is the steady temperature of block A for a given time t. T_0 is the temperature which corresponds with t = 0, T_∞ is the stable temperature of block B and C is the heat capacity of block A.

If the temperature difference is read in terms of voltage and assumed to be proportional to the voltage difference, equation (1) can be written as

$$k = \frac{L}{a} \left[\frac{\tau}{C} \left\{ 1 + \frac{V_{(T_c - T_\infty)}}{V_{(T_c - T_o)}} \right\} \right]^{-1} \tag{2}$$

$$= \frac{L}{a} \left[\frac{\tau}{C} \left\{ 1 + \frac{V_{(T_c - T_\infty)}}{V_{(T_c - T_o)} - V_{(T_c - T_\infty)}} \right\} \right]^{-1}$$

For convenience, equation (2) can be rearranged to give

$$R = \left(\frac{\tau}{C} \right) \left\{ 1 + \frac{V_{(T_c - T_\infty)}}{V_{(T_c - T_o)} - V_{(T_c - T_\infty)}} \right\} \tag{3}$$

$$= \left(\frac{1}{ka} \right) L$$

R is known as the thermal resistance. In practice, equation (3) should be written as

$$R = \left(\frac{1}{ka} \right) L + R_o \tag{4}$$

where R_o represents the contact resistance between the interface of the sample and the blocks.

The voltage difference and τ can be read from the plot produced by a chart-recorder. As an illustration, a typical curve of such a plot is shown in Fig. 1. The thermal resistance, R can therefore be determined from experiments conducted at different values of the sample thickness, L. From equation (4), the plot of R against L will give a slope from which the thermal conductivity of the sample can be determined, i.e. $k = [(slope) \times a]^{-1}$.

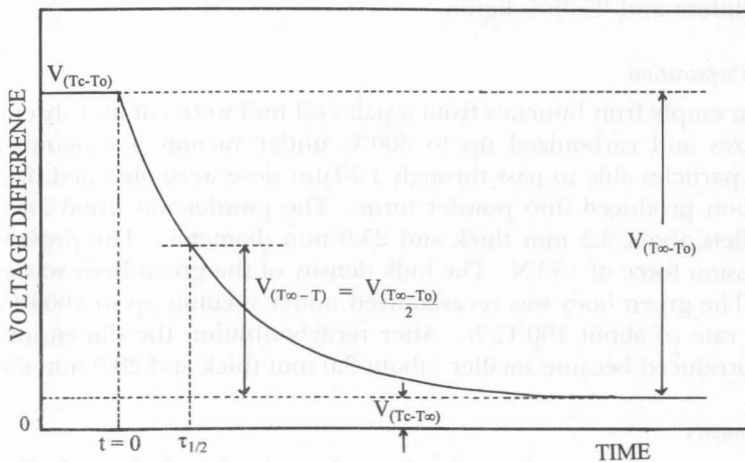


Fig. 1. Typical curve of the voltage difference against time

For a sample composed of solid and pore phases, the resultant thermal conductivity can be written as (Van Vlack 1970)

$$k = k_m = k_c \frac{1 + 2v_p (1 - k_c/k_p) / 2 (k_c/k_p + 1)}{1 - v_p (1 - k_c/k_p) / (k_c/k_p + 1)} \quad (5)$$

where v_p is the volume fraction of the closed pores which are discontinuously dispersed through out the continuous solid phase, k_c and k_p are the thermal conductivities of the solid and pore phases respectively. Since k_p is equal to the thermal conductivity of the air occupied by the pores, then $k_p \ll k_c$. So, equation (5) can be approximated to

$$k_m = k_c \left[\frac{(1 - v_p)}{(1 + v_p)} \right] \quad (6)$$

This equation can be written in terms of the density of the sample as

$$k_m = k_c \left[\frac{2\rho_t}{\rho_b} - 1 \right]^{-1} \quad (7)$$

where ρ_t and ρ_b are the theoretical and bulk density of the sample respectively. This equation can be used to analyse the thermal conductivity data.

MATERIALS AND METHODS

Material

A review of the utilization and some properties of the oil palm empty fruit bunches (EFB) has been reported elsewhere (Mohamad 1993a). EFB consists of bundles of fibres; individual fibres have an average size of about 1 mm long, 25 (μm) and 3 (μm) thick. The nominal chemical composition (%) is: ash (6.3), oil (8.9), C (42.8), N_2 (0.8), P_2O_5 (0.22), K_2O (2.9), MgO (0.3) and CaO (0.25). EFB is a lignocellulosic material which contains 45-50% cellulose, 25-35% hemicellulose and 25-35% lignin.

Sample Preparation

Oil palm empty fruit bunches from a palm oil mill were cut and shredded into small sizes and carbonized up to 300°C under vacuum for about 4 hours. Carbon particles able to pass through a 20- μm sieve were obtained by grinding the carbon produced into powder form. The powder was dried and pressed into pellets about 3.5 mm thick and 25.0 mm diameter. The press used the compression force of 15 kN. The bulk density of the green body was about 1.2 g/cm^3 . The green body was recarbonized under vacuum up to 1000°C using a heating rate of about 100°C/h. After recarbonization the dimensions of the pellets produced became smaller (about 3.0 mm thick and 20.0 mm diameter).

Measurements

The system used for measuring the thermal conductivity is shown in *Fig. 2*. The accuracy of this system in measuring the thermal conductivity of the thin

insulator samples is about 1-3% (Ramli and Low 1991). The temperature difference between blocks A and B was measured using a thermocouple wire connected to a chart-recorder for recording the voltage difference between the blocks against time.

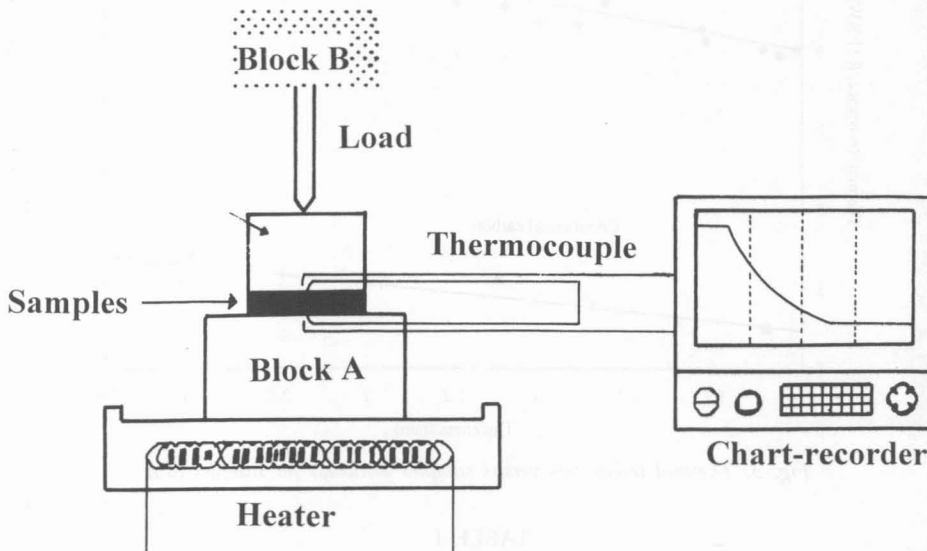


Fig. 2. Schematic diagram of apparatus for the measurement of thermal conductivity by the dynamic method

Mineral oil and a load of about 10 kg were used to improve the contact between the sample and blocks. The temperature of block A was set at a stable temperature of 150°C during the measurement. The measurements were conducted on samples of different thickness.

The dimensions of blocks A and B were 3.00 cm (height) × 5.90 cm (diameter) and 2.00 cm (height) × 2.00 cm (diameter) respectively. The density and heat capacity of the blocks were 2.70 g cm⁻³ and 15 J K⁻¹ respectively.

RESULTS AND DISCUSSION

The time, τ and the voltages, $V_{(T_c - T_o)}$ and $V_{(T_c - T_o)}$, obtained from the plot of voltage difference against time for each sample thickness are shown in Table 1 for both carbon-EFB and carbon-A. Using equation (3) and the data in Table 1, the thermal resistance R was calculated and the results are also shown in Table 1. The plots of R against L for the carbon-EFB and carbon-A are shown in Fig. 3. Although the points for R appear to be spread out they occur around a straight line which can intercept the R -axis. This behaviour is consistent with equation (4) and therefore the R_o values can be determined from the graphs. The values obtained were 6.65 KW⁻¹ and 0.67 KW⁻¹ for carbon-EFB and carbon-A respectively.

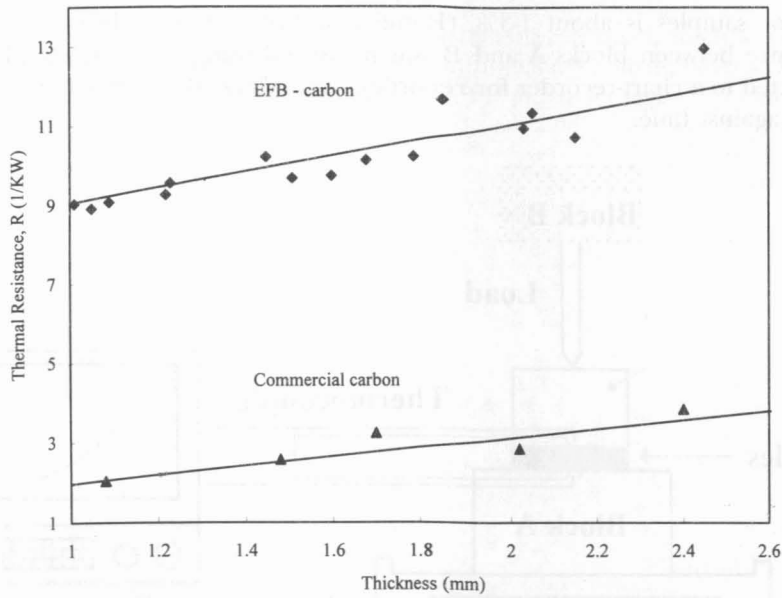


Fig. 3. Thermal resistances versus samples thickness for samples EFB

TABLE 1

Values of thermal resistance, R (calculated using equation (3)) and measured values of τ and voltage difference for different values of the sample thickness, L. No. 1-15 are samples prepared from EFB and no. 16-20 are samples of commercial carbon-A

No.	L(mm) ± 0.01	τ (s) ± 0.5	$V(T_c - T_o)$ (mV) ± 0.05	$V(T_c - T_\infty)$ (mV) ± 0.05	R(KW ⁻¹) ± 0.05
1	1.01	79.5	10.20	1.64	9.03
2	1.05	78.0	9.60	1.60	8.91
3	1.09	82.5	11.52	1.32	9.07
4	1.22	82.5	9.84	1.48	9.26
5	1.23	84.0	9.92	1.60	9.55
6	1.45	88.5	9.68	1.68	10.21
7	1.51	84.0	10.00	1.72	9.67
8	1.60	85.5	9.84	1.60	9.73
9	1.68	90.0	10.00	1.52	10.12
10	1.79	95.0	9.68	1.36	10.22
11	1.85	100.5	10.12	1.80	11.66
12	2.03	93.0	11.12	1.92	10.94
13	2.05	99.0	9.60	1.60	11.33
14	2.15	92.4	9.68	1.72	10.71
15	2.45	112.5	9.76	1.68	12.96
16	1.08	20.0	9.76	0.48	2.04
17	1.48	25.5	9.68	0.52	2.57
18	1.70	32.0	9.80	0.56	3.24
19	2.02	28.2	9.80	0.56	2.85
20	2.40	37.8	9.84	0.64	3.85

TABLE 2

Values of thermal conductivities. M is measured from the present experiment, PB and PC are the predicted values using the k_c values estimated from samples B and C respectively (*values quoted by the manufacturer, \dagger density = sample weight/sample volume, \ddagger Porosity = $[1-(\text{bulk density of sample})/(\text{theoretical density of graphite})]$).

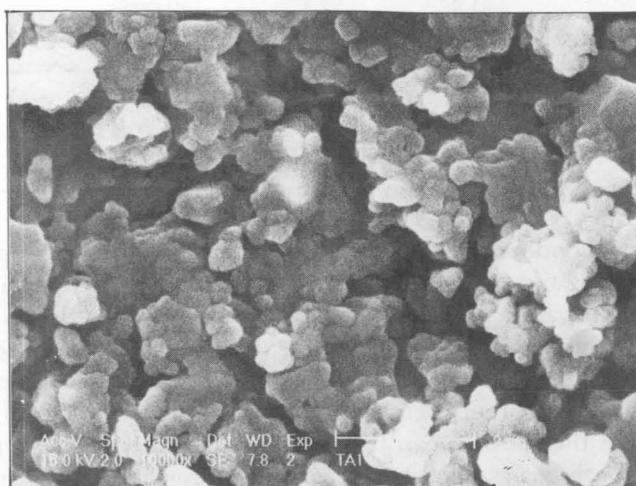
Parameters	Carbon samples			
	B	C	A	EFB
Bulk density (g cm^{-3})	1.54*	1.42*	1.59 \dagger	1.15 \dagger
Porosity (%)	31.86 \ddagger (closed)	37.17 \ddagger (closed)	29.65 \ddagger (closed + open)	49.12 \ddagger (closed + open)
Thermal conductivity k_m ($\text{Wm}^{-1}\text{K}^{-1}$) at 150°C	5.0*	7.5*	2.55 (M) 5.25 (PB) 7.87 (PC)	1.38 (M) 3.30 (PB) 4.95 (PC)

The thermal conductivities obtained from the slope of the graphs in *Fig. 3* for the carbon-EFB and carbon-A are shown in Table 2. These values can be compared with the values predicted using equation (7). In order to predict the values of k_m for carbon-EFB and carbon-A, the values of k_c in equation (7) were estimated using the known values of k_m and ρ_b for carbons-B and C (Table 2) and the value of theoretical graphite density ($\rho_t = 2.26\text{g cm}^{-3}$). The use of these samples for this purpose can be regarded as justified because they consist of only closed pores, as claimed by the manufacturer and also as indicated by the SEM micrograph in *Plate 1*. With this estimated k_c value, the thermal conductivity of carbon-EFB and carbon-A were predicted using equation (7). The predicted values shown in Table 2 seem to be higher than the measured values by factors of 2-5. This difference is expected because the formula used for prediction is only valid for samples with a discontinuous phase, which is obviously not the microstructure of carbon-EFB and carbon-A. As can be seen in the SEM micrograph (*Plate 1*), these samples consist of interconnected pores and therefore they do not exactly act as a discontinuous phase.

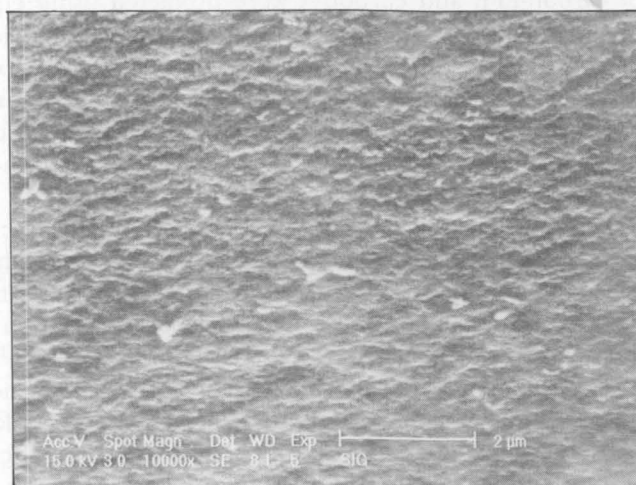
Under these conditions and considering that the volume fraction of the pore phase is relatively high, the contribution from the air in the pores in reducing the resultant conductivity, k_m , is very significant because the thermal conductivity of air is very small compared to that of solid carbon phase, for example, at room temperature (30°C), its value is about $0.03\text{ Wm}^{-1}\text{K}^{-1}$. From the above analysis, it can be concluded that the predicted values are not accurate for both samples, carbon-EFB and carbon-A. However, the formula used may be regarded as useful in giving a rough estimation of the thermal conductivity of the carbon samples which consist of both type of pores, i.e. open and closed pores.

Table 2 shows that the thermal conductivity of the samples does not systematically vary with the volume fraction of the pore phase. This indicates

that the percentage of porosity reflects only one of the determining factors for the samples' conductivity, which is not always necessarily being the main factor. Such a percentage does not actually take into account other factors, for example, the characteristics of the form of porosity as well as the properties of the solid carbon phase such as the bonding between particles resulting from sintering processes, crystallite dimensions and the atomic arrangements of the samples. These factors are significant because they may influence the phonon conduction in the samples, which is the main mechanism responsible for the thermal conductivity of the samples.



(a)



(b)

Plate 1. SEM-micrographs for samples (a) EFB-carbon and (b) Commercial carbon (B)

As can be seen in Table 2, the thermal conductivity of carbon-EFB is lower than the other samples. The SEM micrographs in *Plate 1* clearly show that carbon-EFB is much more porous than the other samples, as is also by its 50% porosity. This high level of porosity could have contributed towards lowering the thermal conductivity of carbon-EFB. Therefore, to achieve the values of the thermal conductivity of the commercial samples, the microstructure as well as the density of carbon-EFB have to be substantially improved.

CONCLUSION

The thermal conductivity of the carbon samples prepared from fibres of oil palm empty fruit bunches has been measured and compared with (i) the measured thermal conductivity of the commercial carbon samples with closed and open pores, (ii) the quoted thermal conductivity of the commercial carbon samples with only closed pores and (iii) the values of the thermal conductivity predicted using the formula for samples having two phases (continuous and discontinuous). From this comparison, it can be concluded that (i) carbon-EFB has the lowest thermal conductivity due to its higher content of open porosities (ii) it is acceptable to use the formula as well as the value of k_c from samples without open porosity to predict the approximation of thermal conductivity (iii) the measurement technique of Lee (1982) used in this work is reliable.

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