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Electromagnetic shielding efficiency of the electric field of charcoal from six wood species

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Abstract Six wood species were carbonized under various carbonization temperatures and nonoxygen conditions to obtained charcoal. The effects of wood species, rate of temperature rise, and carbonization temperature on the electromagnetic shielding efficiency (ESE) of the electric field were investigated. The wood species used in this study were Japanese cedar, China fir, western hemlock, red oak, fortune paulownia, and Taiwan acacia. Tested materials were carbonized in a high-temperature oven under the following conditions: rate of temperature rise 1°–5°C/min; carbonization temperature 500°–1100°C, with temperature intervals of 100°C; maximum temperature maintained for 1 h; and flow rate of nitrogen 300 ml/min. The electromagnetic insulation strength system was used to detect the ESE of the electric field of charcoal. It was found that western hemlock and fortune paulownia charcoal showed maximum ESE values of of 36 and 61 dB generated at a carbonization temperature of 1000°C. The charcoals derived from four other wood species showed maximum ESE values of 28 dB for Japanese cedar, 23 dB for China fir, 32 dB for red oak, and 38 dB for Taiwan acacia, respectively, at a carbonization temperature of 1100°C. The ESE value for fortune paulownia charcoal was similar to those of metal nets. The relations between ESE and logarithmic values of resistivity ($\log \rho$) could be represented by a negatively exponential formula.

Key words Electromagnetic shielding efficiency (ESE) · Charcoal · Carbonization temperature · Rate of temperature rise · Resistivity

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Introduction

With progress in science and technology, a large number of electronic products have come into use, such as computers, microwave ovens, televisions, and so on. These products introduce an electromagnetic interference (EMI) problem because electric machines produce an electric field and electric current that generate a magnetic field. In other words, when we use electric machines and enjoy these conveniences, they introduce an electromagnetic environmental crisis.

Studies on charcoal have been well developed for decades. Charcoal is the chief product of wood pyrolysis, and the main uses of charcoal can be divided into fuel, metallurgical, and chemical purposes. The application of electromagnetism is one use in the metallurgical field. High-performance properties of charcoals carbonized under various temperatures have been identified. Based on the research of Ishihara, when a heating temperature reaches the stage of "carbonization" (about 800°–1700°C), charcoal can be used as an electromagnetic shielding material.[1] Generally speaking, electromagnetic shielding efficiency (ESE) is directly proportional to the electric and magnetic properties of the materials.

The purpose of this study was to manufacture a low-cost charcoal that exhibits such properties as light weight, stability, and high ESE. Moreover, it could replace other conducting materials and be biologically friendly and renewable. The charcoals made from six wood species under various carbonized temperatures were used in this study. The resistivity and ESE of the electric field of charcoal were explored.

Materials and methods

Wood materials

The charcoals of six wood species including Japanese cedar [*Cryptomeria japonica*, specific gravity (sp. gr.) 0.54], China fir (*Cunninghamia lanceolate*, sp. gr. 0.35), western hemlock (*Tsuga heterophylla*, sp. gr. 0.44), red oak (*Quercus* sp., sp. gr. 0.69), fortune paulownia (*Paulownia fortunei*, sp. gr. 0.30), and Taiwan acacia (*Acacia confusa*, sp. gr. 0.88) were used in this study.

Preparation of charcoal specimens

Wood specimens were cut from wood waste into 5.0 × 5.0 × 1.2 cm specimens. They were then conditioned in a chamber at 20°C and 65% relative humidity (RH) until their moisture content reached 12% ± 1%. Wood specimens were carbonized in a high-temperature oven under the following conditions: rate of temperature rise 1°–5°C/min, at a rate of 1°C/min; carbonization temperature 500°–1100°C, at intervals of 100°C; maximum temperature maintained for 1 h; flow rate of nitrogen 300 ml/min. The charcoal specimens were sanded to 3.0 × 3.0 × 0.8 cm, and several charcoal specimens were glued on plywood (3 mm thick) to make a specimen 10.0 × 15.0 × 1.1 cm. All charcoal specimens were conditioned in a chamber at 20°C and 65% RH until their moisture content reached 12% ± 1%.

Metal net

Three kinds of metal net were used in this study for comparison with the charcoal specimens: iron net (60 mesh, 5.5 mm thick), copper net (60 mesh, 2.0 mm thick), and steel net (60 mesh, 1.5 mm thick). All were cut into 10.0 × 15.0 × 1.1 cm specimens.

Resistivity of charcoal specimens

An HP 3478A digital multimeter was used to measure electric resistance from 0.0001 Ω to 30 MΩ. The electric resistance (R) of charcoal was measured (direction of measurement to wood fiber) using a two-wire ohms configuration.[2] Resistivity (ρ) was calculated from Eq. (1).

$$\rho = (R \cdot A)/d \tag{1}$$

where ρ is the resistivity (Ω·cm); R is the electric resistance (Ω); A is the cross-sectional area of the charcoal specimen (cm^2); and d is the distance between electrodes (cm).

ESE of electric field of charcoal

The electromagnetic insulation strength system was used to detect the ESE of charcoal. The equipment (Fig. 1) used in this study includes Wilton Company product 54111A type Net Analyzer, R-band type of insertion loss (IL) sheet tester for measuring fixture (Damasko), detector with 1.5–2.7 GHz frequency, and stand wave ratio (SWR) auto tester with 50 Ω. The ESE was derived from Eq. 2.

$$\mathrm{ESE(dB)} = 20\log(Eo/Es) \tag{2}$$

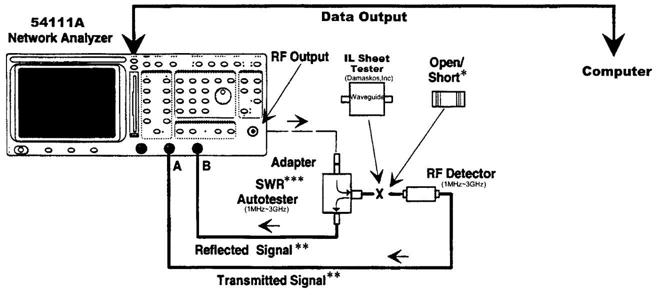

Fig. 1. Electromagnetic insulation strength measurement system. *RF*, radiofrequency; *connect during calibration; **detected signals; ***standing wave ratios; #if required

where Eo is the incident electric field intensity (intensity without sample) (v/m); and Es is the transmission electric field intensity (intensity with sample) (v/m).

The evaluation standard for ESE is divided into five classes[3] as follows.

0–10 dB: very little shielding
10–30 dB: minimum shielding
30–60 dB: average shielding
60–90 dB: above average shielding
90–120 dB: maximum to beyond existing state-of-the-art shielding

Results and discussion

Resistivity of charcoal

The resistivity (ρ) values of various charcoals made from six wood species with a rate of temperature rise of 3°C/min are shown in Table 1. It was found that the ρ values ranged from 10^8 to 10^2 Ω·cm for Japanese cedar; 10^8 to 10^1 Ω·cm for China fir; 10^7 to 10^{-1} Ω·cm for western hemlock, red oak, and Taiwan acacia; and 10^7 to 10^0 Ω·cm for fortune paulownia. The ρ values decreased with increasing carbonization temperature, with a significant reduction at certain carbonization temperatures as follows: 1000°C for China fir; 900°C for fortune paulownia and Japanese cedar; 800°C for western hemlock; and 700°C for red oak and Taiwan acacia (Fig. 2). These results were in good agreement with previous reports.[1,4,5]

Okabe et al.[6] investigated the resistivity of wood ceramics and indicated that the resistivity of wood ceramics ranged from 10^{10} to 10^{-3} Ω·cm at 400°–2800°C carbonization temperatures. Our results are similar to theirs.

ESE of electric field of charcoal

The ESE of charcoal from six wood species (8 mm thick) carbonized at various temperatures (500°–1100°C) is presented in Table 2. It was found that the ESE values for various wood charcoals increased with increasing carbonization temperature. The maximum ESE values were 36 and 60 dB for western hemlock and paulownia charcoal,

Table 1. Resistivity (ρ) of various charcoals made from six wood species

Carbonization temperature (°C)	Resistivity (Ω·cm)					
	Japanese cedar	China fir	Western hemlock	Red oak	Taiwan acacia	Fortune paulownia
500	5.6×10^{8}	1.8×10^{8}	9.6×10^{6}	1.3×10^{7}	1.4×10^{7}	1.2×10^{7}
600	2.5×10^{8}	8.1×10^{6}	1.0×10^{7}	6.3×10^{6}	1.3×10^{7}	7.1×10^{6}
700	1.6×10^{8}	6.3×10^{6}	7.6×10^{6}	6.6×10^{2}	5.6×10^{3}	6.9×10^{6}
800	2.5×10^{8}	2.9×10^{6}	2.6×10^{0}	3.8×10^{0}	4.9×10^{0}	5.1×10^{6}
900	4.7×10^{5}	1.6×10^{6}	7.7×10^{-1}	1.0×10^{0}	7.4×10^{-1}	1.2×10^{1}
1000	2.3×10^{2}	1.6×10^{1}	6.8×10^{-1}	4.3×10^{-1}	3.4×10^{-1}	1.5×10^{0}

Table 2. Electromagnetic shielding efficiency of charcoal from six wood species

Carbonization temperature (°C)	ESE (dB)					
	Japanese cedar	China fir	Western hemlock	Paulownia	Red oak	Acacia
25[a]						
Avg.	1.90 ± 0.60	1.79 ± 0.58	2.62 ± 0.72	1.28 ± 0.62	4.71 ± 1.32	3.36 ± 0.84
CV	19.1	19.1	20.0	30.3	37.1	20.9
500						
Avg.	0.99 ± 0.48	0.91 ± 0.43	0.98 ± 0.47	1.17 ± 0.54	1.34 ± 0.59	1.17 ± 0.57
CV	23.7	19.8	23.0	24.9	26.0	27.6
600						
Avg.	1.24 ± 0.56	1.03 ± 0.57	0.93 ± 0.40	1.31 ± 0.63	1.23 ± 0.54	1.25 ± 0.53
CV	25.4	31.5	17.4	30.7	23.5	22.1
700						
Avg.	3.69 ± 1.05	1.13 ± 0.61	0.85 ± 0.43	1.60 ± 0.38	13.66 ± 1.10	6.79 ± 3.09
CV	29.7	32.6	21.8	9.2	8.8	140.8
800						
Avg.	1.25 ± 0.43	19.01 ± 1.62	33.33 ± 2.25	2.74 ± 0.72	31.69 ± 1.40	28.78 ± 1.38
CV	15.0	13.9	15.3	18.9	6.2	6.6
900						
Avg.	8.56 ± 1.34	13.23 ± 4.05	27.79 ± 1.55	31.82 ± 2.83	26.53 ± 2.15	34.34 ± 1.65
CV	21.0	124.2	8.7	25.2	17.4	8.0
1000						
Avg.	24.86 ± 1.44	22.57 ± 1.09	36.11 ± 2.22	60.62 ± 5.19	27.71 ± 1.26	37.18 ± 2.68
CV	8.37	5.3	13.7	44.4	5.7	19.4
1100						
Avg.	27.61 ± 0.96	22.70 ± 2.20	32.25 ± 0.99	41.97 ± 3.81	32.47 ± 0.98	38.38 ± 5.00
CV	3.8	5.8	3.1	34.6	3.0	65.3

Frequency of ESE measurement 1.5–2.7 GHz
Results are averages ± SD
ESE, electromagnetic shielding efficiency; Avg., average; CV, coefficient of variation (%) (standard deviation/average values × 100)
[a] Untreated

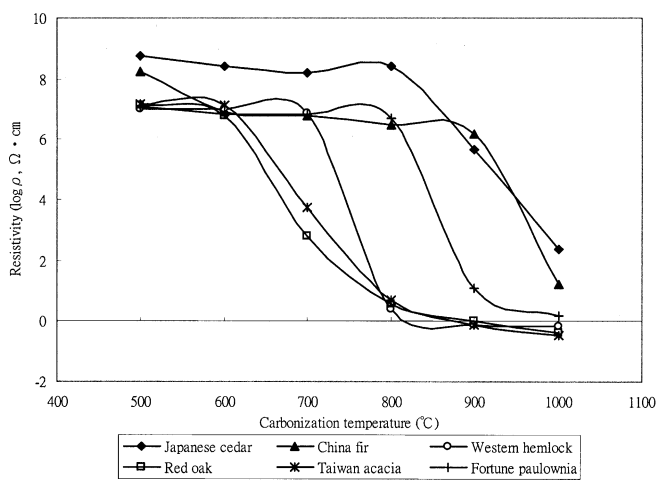

Fig. 2. Relations between carbonization temperature (T) and resistivity of charcoal from six wood species (rate of temperature rise was 3°C/min)

respectively, at 1000°C carbonization temperature; they were 37, 22, 32 and 38 dB for Japanese cedar, China fir, red oak and Acacia charcoal, respectively, at 1100°C carbonization temperature, as shown in Fig. 3. These values were comparable to the ESE value for 60-mesh metal net (Fig. 4), which had average ESE. In contrast, the ESE values for solid wood were only 1.3–4.7 dB and exhibited the behavior of an insulation material.

The effects of the rate of temperature rise on the ESE values of fortune paulownia charcoal obtained at the maximum temperature of 1000°C is shown in Fig. 5. It was obvious that the ESE values decreased with an increasing rate of temperature rise. This means that the lower rate of temperature rise for fortune paulownia charcoal exhibited better ESE, whereas the ESE values at less than 3°C/min rate of temperature rise for charcoal showed the same level as metal net materials.

In general, materials exhibiting lower values of resistivity had larger ESE values. This is because when the resistivity

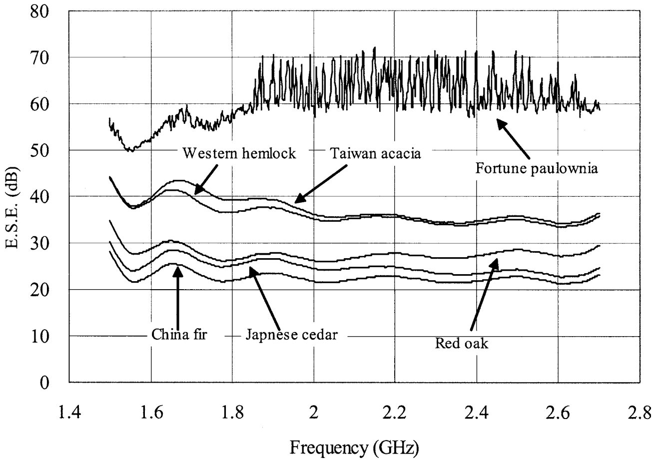

Fig. 3. Electromagnetic shielding efficiency (*ESE*) of electric field of charcoal from six wood species at 1000°C carbonization temperature

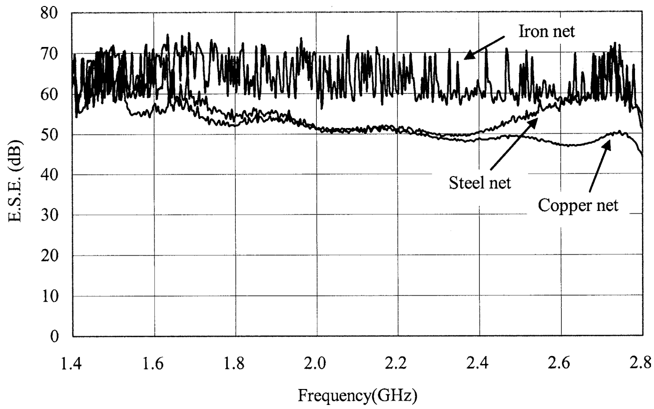

Fig. 4. Electromagnetic shielding efficiency of electric field of three metal nets of 60 mesh

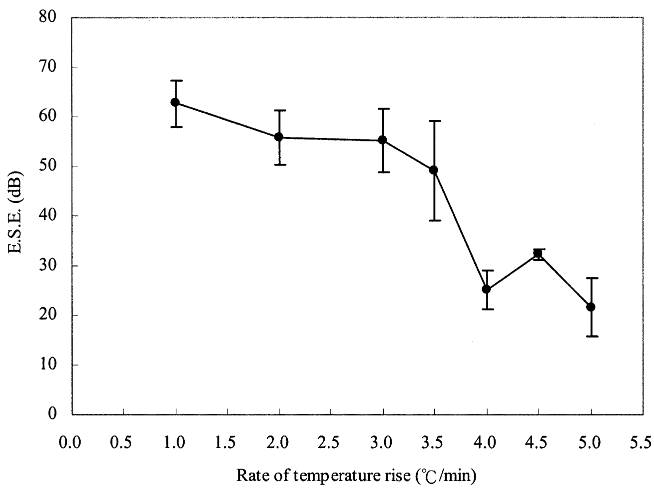

Fig. 5. Relations between the rate of temperature rise and ESE of electric field of fortune paulownia charcoal (carbonization temperature 1000°C, charcoal thickness 8 mm)

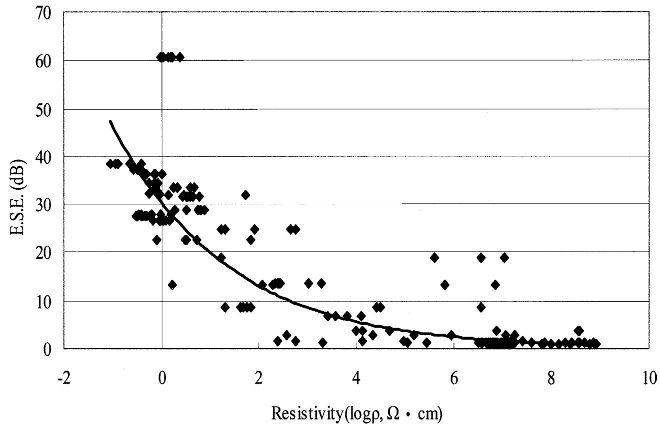

Fig. 6. Relations between electric resistivity ($\log \rho$) and ESE of electric field of charcoals from six wood species

Table 3. Relations between ESE values and logarithm values of resistivity ($\log \rho$)

Charcoal board	Semilogarithm formula	
	ESE	R^2
Japanese cedar	$21.42\ e^{-0.32 \log \rho}$	0.667*
China fir	$29.47\ e^{-0.37 \log \rho}$	0.592*
Western hemlock	$31.28\ e^{-0.51 \log \rho}$	0.992*
Fortune paulownia	$35.15\ e^{-0.43 \log \rho}$	0.864*
Red oak	$30.92\ e^{-0.44 \log \rho}$	0.959*
Taiwan acacia	$31.68\ e^{-0.45 \log \rho}$	0.991*

*Highly significant difference at 0.01 confidence level by *F* value test

decreased significantly the materials changed from insulating material to semiconducting material; they thus became conducting materials. The ESE values for Japanese cedar and China fir charcoal were 25 and 23 dB when their charcoal resistivity values decreased to 10^2–$10^1\ \Omega\cdot$cm; the ESE values for western hemlock and red oak charcoal were 33 and 32 dB when their charcoal resistivity values decreased to $10^{-1}\ \Omega\cdot$cm; and the ESE values of fortune paulownia and Taiwan acacia charcoal were 61 and 37 dB when their charcoal resistivity values decreased to 10^0–$10^{-1}\ \Omega\cdot$cm. Okabe et al.[6] indicated that the wood ceramics exhibited $10^{-2}\ \Omega\cdot$cm of resistivity and a 49 dB ESE value at less than 300 MHz.

When the relations between the ESE value and resistivity (ρ) were investigated for the charcoal of each wood species, their relation could be represented by negatively exponential formulas, as shown in Table 3. When the data obtained from the charcoals of six wood species were analyzed, the relations also could be represented by the following negatively exponential formula (shown in Fig. 6).

$$\mathrm{ESE} = 30.349 e^{-0.421 \log \rho}, \; R^2 = 0.843 \tag{3}$$

It is obvious that a negatively exponential formula exists between the ESE value and the resistivity of charcoal. This suggested that the ESE values of charcoal were influenced by its resistivity. When its resistivity was low, it was close to the conductivity performance and exhibited better ESE;

therefore, decreasing the resistivity of charcoal would result in its increased ESE.

This result was in good agreement with the previous results reported by Ide et al.[7] in which the ESE of Japanese cedar thinning wood charcoal increased with increasing carbonization temperature; its high performance was compared with the standard metal plate at 1000°C. Furthermore, the ESE of charcoal carbonized at 1200°C was higher than that for graphite material. Okabe et al.[6,8] also indicated that the resistivity values of wood ceramics would change from those of an insulating material to those of a conductive material by increasing the carbonization temperature, and the ESE would then be influenced by its resistivity. The electric shielding effect and magnetic shielding effect occur over 873 K and 973 K carbonization temperatures, respectively.

Conclusions

The resistivity (ρ) of charcoal from six wood species decreased with increasing carbonization temperature, from 500°C to 1100°C. Depending on the wood species, the resistivity decreased from 10^8–$10^{10}\Omega\cdot$cm to 10^0–$10^{-1}\Omega\cdot$cm; and the resistivity rapidly decreased when the carbonization temperature reached 700°–900°C.

The maximum ESE values for charcoal were 28 dB for Japanese cedar, 23 dB for China fir, 36 dB for western hemlock, 61 dB for fortune paulownia, 32 dB for red oak, and 38 dB for Taiwan acacia. The ESE of charcoal increased with decreasing resistivity. It could be represented by a negatively exponential formula. The ESE of fortune paulownia charcoal decreased with an increasing rate of temperature rise. The best interval was 1°C/min.

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