

# Electrical and mechanical properties of electrically conductive polyethersulfone composites

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Electrically conductive polyethersulphone (PES) composites containing carbon fibres, nickel fibres, stainless steel fibres or aluminium flakes at various volume fractions up to 40% were fabricated and tested. For electromagnetic interference (EMI) shielding effectiveness  $> 50$  dB, the minimum filler volume fraction was 40% for carbon fibres of length 200 or 400  $\mu\text{m}$ , 20% for nickel or stainless steel fibres, and 30% for aluminium flakes. The tensile strength first increased and then decreased with increasing filler content, such that the highest tensile strength occurred at 30 volume% (vol%) for carbon fibres (of length 200 or 400  $\mu\text{m}$ ) as the filler and at 10 vol% for nickel or stainless steel fibres. However, for carbon fibres (of length 100  $\mu\text{m}$ ) and aluminium flakes, the tensile strength increases up to at least 40 vol%. The best overall performance was provided by aluminium flakes at 40 vol%; the resistivity was  $7 \times 10^{-5} \Omega \text{ cm}$ , the EMI shielding effectiveness was  $> 50$  dB and tensile strength was 67 MPa. The resistivity of the aluminium flake composites was not affected by heating in air at 140°C for up to at least 144 h.

**Key words:** *polymer composites; electromagnetic interference; shielding; electrical resistivity; polyethersulfone; carbon fibres; nickel fibres; stainless steel fibres; aluminium flakes; heating*

Electrically conductive polymer-matrix composites are replacing metal sheets for electronic housings which can shield electromagnetic interference (EMI). This is because of the mouldability of the composites. The requirement for shielding is becoming more and more stringent as electronics become more sensitive and abundant.

The choice of conductive fillers is critical to the electrical and mechanical properties of the composites. Fillers that have shown most promise include stainless steel fibres<sup>1,2</sup>, carbon fibres<sup>1,4</sup>, nickel-plated carbon fibres<sup>3</sup> and aluminium flakes<sup>1,3,5</sup>. It was reported that, to obtain composites with electrical resistivity of 1  $\Omega \text{ cm}$  and EMI shielding effectiveness of 40 dB: (1) polyacrylonitrile (PAN) based carbon fibres as a filler gave composites of the highest mechanical strength and stiffness; (2) stainless steel fibres were effective at the lowest volume fractions (even 1–2 volume% (vol%)); and (3) aluminium flakes were the most economical<sup>1</sup>. Moreover, it was reported that aluminium flakes were less effective as a reinforcement

than the fibres<sup>1</sup>. In the case of polyvinylchloride (PVC) as the matrix, the addition of aluminium flakes decreased the flexural strength<sup>5</sup>.

This paper presents a systematic study of the electrical and mechanical properties of polyethersulfone (PES) filled with stainless steel fibres, nickel fibres, pitch-based carbon fibres and aluminium flakes at various volume fractions. We found that different fillers at various volume fractions differ greatly in their effects on the electrical and mechanical properties; a certain filler at a certain volume fraction may enhance the electrical properties but degrade the mechanical properties. In contrast to previous studies<sup>1,5</sup>, we found that, at a filler content of 20 vol%, aluminium flakes were more effective as a reinforcement than carbon, stainless steel or nickel fibres. Aluminium flakes at 40 vol% gave a composite exhibiting the best overall performance; i.e., high tensile strength ( $> 67$  MPa) and modulus ( $> 16$  GPa), low electrical resistivity ( $6.6 \times 10^{-5} \Omega \text{ cm}$ ) and high EMI shielding effectiveness ( $> 50$  dB). Furthermore, the resis-

tivity was not affected by heating in air at 140°C for up to at least 144 h.

## BACKGROUND

### Theory of the electrical resistivity of a composite

For a continuous unidirectional fibre composite, the rule of mixtures can be applied for calculating the resistivity. That is,

$$\frac{1}{\rho_c} = \frac{V_f}{\rho_f} + \frac{V_m}{\rho_m} \quad (1)$$

where  $\rho$  is the electrical resistivity,  $V$  is the volume fraction of a particular component, and the subscripts c, f and m refer to the composite, fibre and matrix, respectively.

For short fibre-filled composites, the theory is different from that for a unidirectional composite system. Based on probability theory, the minimum resistivity ( $\rho_{\min}$ ) that can be achieved for an oriented (along the electric field) short fibre-filled composite having fibre resistivity  $\rho_f$  and volume fraction  $V_f$  is given by<sup>6</sup>:

$$\rho_{\min} = \frac{\rho_f}{V_f} \quad (2)$$

Because of the contribution of fibres oriented at an angle to the electric field, the resistivity of a composite containing randomly oriented fibres is higher, and given by<sup>6</sup>:

$$\rho_{\min} = \frac{3\pi\rho_f}{2V_f} \quad (3)$$

### Theory of reinforcement in a composite

The reinforcement of polymeric materials results in the distribution of an applied stress between the matrix and the reinforcement. A number of theoretical relations can be used for predicting the properties of the composites<sup>7-9</sup>. Such relations include the Halpin-Tsai<sup>10</sup> equations, which predict the mechanical properties of particulate, as well as continuous and discontinuous fibre-reinforced polymers.

For particulate composites, the modulus  $E$  is predicted by the Halpin-Tsai equation, due to the isotropic nature of particulate fillers. For rigid, spherical, isotropic and randomly dispersed particles, the following equation is proposed for the modulus of the composite<sup>11</sup>:

$$E_c = E_m(1 + 2AV_f)/(1 - AV_f) \quad (4)$$

where

$$A = (E_f/E_m - 1)/(E_f/E_m + 2)$$

For short fibre composites, the composite modulus can be predicted by using the equations derived from the Halpin-Tsai equations. For a unidirectional, discontinuous fibre-reinforced polymer, the longitudinal modulus ( $E_L$ ) and the transverse modulus ( $E_T$ ) of the composite are given by the equations<sup>12</sup>:

$$E_L = E_m[1 + 2(L/D)N_L V_f]/(1 - N_L V_f) \quad (5)$$

and

$$E_T = E_m(1 + 2N_T V_f)/(1 - N_T V_f) \quad (6)$$

where

**Table 1. Properties of polyethersulfone polymer**

Glass transition temperature (°C)	220–222
Density (g cm <sup>-3</sup> )	1.37
Particle size (µm)	100–150
Tensile strength (MPa)	45.93 ± 1.12
Tensile modulus (GPa)	2.64 ± 0.19
Elongation at break (%)	(3.1 ± 0.3)
Electrical resistivity (Ω cm)	> 10 <sup>10</sup>
Coefficient of thermal expansion (K <sup>-1</sup> )	55 × 10 <sup>-6</sup>

$$N_L = [(E_f/E_m) - 1]/[(E_f/E_m) + 2(L/D)]$$

$$N_T = [(E_f/E_m) - 1]/[(E_f/E_m) + 2]$$

and  $L/D$  is the aspect ratio of the fibres.

For a composite containing randomly oriented discontinuous fibres and exhibiting planar isotropic behaviour, the tensile modulus ( $E_{\text{random}}$ ) is given by<sup>12</sup>:

$$E_{\text{random}} = \frac{3}{8} E_L + \frac{5}{8} E_T \quad (7)$$

## EXPERIMENTAL

### Materials

The polymer used was PES, a thermoplastic (Victrex PES 4100P, from ICI). The properties of this polymer are shown in Table 1.

The aluminium flakes were of size 1.2 × 1.0 × 0.03 mm, as provided by Transmet Corp. The carbon fibres were short, isotropic-pitch-based and unsized, provided by Ashland Petroleum Co as Carboflex; they were 10 µm in diameter and 100, 200, 400, 800 or 3000 µm long. The mechanical properties of such pitch-based carbon fibres are inferior to those of PAN-based carbon fibres, but they are much less expensive. Also used were PAN-based carbon fibres (Hercules, IM6), which were unsized and of diameter 10 µm and length 100 µm. The nickel fibres were 20 µm in diameter and 1000 µm long, and were provided as Fibrex by National-Standard Co. The stainless steel fibres had a diameter of 30–56 µm and a length of 1590 µm, and were provided by International Steel Wool Corp.

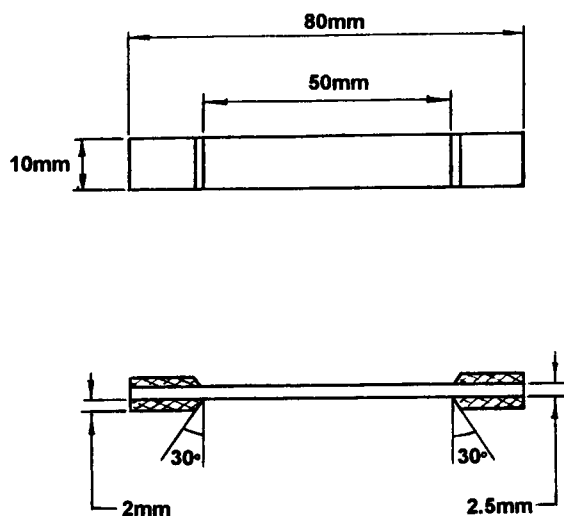


Fig. 1 Tensile test specimen geometry



**Table 3. Tensile properties of PES composites**

Filler	Vol% filler	Strength (MPa)	Modulus (GPa)	Elongation (%)
–	0	45.93 ± 1.12	2.64 ± 0.19	3.10 ± 0.30
PAN carbon fibres (100 µm)	10	48.90 ± 0.16	3.17 ± 0.04	2.31 ± 0.02
Pitch carbon fibres (100 µm)	10	47.34 ± 1.03	3.50 ± 0.21	2.35 ± 0.23
	20	50.75 ± 1.55	4.45 ± 0.43	1.76 ± 0.21
	30	57.46 ± 2.02	6.30 ± 0.19	1.44 ± 0.07
	40	60.19 ± 2.31	7.21 ± 0.06	0.93 ± 0.11
Pitch carbon fibres (200 µm)	10	52.73 ± 0.37	3.62 ± 0.21	2.03 ± 0.02
	20	57.92 ± 1.47	4.54 ± 0.03	1.41 ± 0.04
	30	65.84 ± 1.73	6.31 ± 0.51	1.01 ± 0.05
	40	61.69 ± 2.36	7.73 ± 0.41	0.90 ± 0.11
Pitch carbon fibres (400 µm)	10	54.92 ± 0.52	3.71 ± 0.12	2.08 ± 0.11
	20	60.88 ± 2.03	4.96 ± 0.01	1.69 ± 0.03
	30	73.92 ± 0.81	5.93 ± 0.29	1.31 ± 0.01
	40	66.10 ± 1.03	8.10 ± 1.12	0.86 ± 0.03
Pitch carbon fibres (800 µm)	10	56.64 ± 0.63	3.84 ± 0.07	2.01 ± 0.21
	20	62.09 ± 1.00	5.75 ± 0.42	1.37 ± 0.17
Pitch carbon fibres (3000 µm)	5	48.46 ± 0.70	3.46 ± 0.15	2.14 ± 0.11
	10	51.15 ± 1.20	3.77 ± 0.61	1.81 ± 0.30
	15	57.00 ± 3.10	4.70 ± 0.41	1.58 ± 0.12
	20	64.33 ± 2.23	5.78 ± 0.36	1.35 ± 0.08
Nickel fibres	10	54.44 ± 0.07	3.65 ± 0.26	1.65 ± 0.24
	20	50.50 ± 1.33	4.25 ± 0.18	1.40 ± 0.15
Stainless steel fibres	10	60.96 ± 1.75	4.66 ± 0.18	1.55 ± 0.21
	20	44.19 ± 0.45	5.72 ± 0.57	1.10 ± 0.02
Aluminium flakes	5	48.49 ± 2.92	3.49 ± 0.08	1.85 ± 0.19
	10	56.47 ± 4.93	3.88 ± 0.06	1.47 ± 0.25
	15	63.95 ± 4.30	4.81 ± 0.63	1.34 ± 0.11
	20	65.07 ± 2.71	5.22 ± 0.39	1.28 ± 0.10
	30	65.92 ± 1.58	8.50 ± 0.20	0.92 ± 0.21
	40	67.23 ± 0.49	15.53 ± 0.27	0.60 ± 0.02

### Composite fabrication

Composites were fabricated by mixing the polymer powder and the filler and then hot-pressing the mixture in a matched-metal die at 4.90 MPa and 310°C for 20 min.

### Composite characterization

Electrical resistivity measurements were made on composite materials which had been cut into bars. The four probe method was used. Four specimens of each composition were tested. Four data points were obtained for each specimen.

The EMI shielding effectiveness was measured at 1.0–2.0 GHz using the coaxial cable method. The sample was in the form of an annular disc, of outside and inside diameter 97.4 and 28.8 mm, respectively; the thickness ranged from 2.82 to 2.95 mm. In order to get a continuous metallic contact between the sample and the steel shielding tester chamber, conductive silver paint was applied to the inner surface of the centre hole of the sample and the outer rim of the annular disc. Two speci-

mens of each composition were tested. The set-up was capable of measuring attenuations up to 50 dB only.

The tensile test specimen geometry is illustrated in Fig. 1. The specimens were precision machined from plates with tabs bonded in place. Test specimen edges were undamaged and parallel. The specimens were tested mechanically using standard methods and a Materials Testing System (MTS). An IBM-PS-2 computer with OPUS-200 software and a data acquisition board were used for the data collection. EA-13-120LZ-120 (Measurements Group, Inc) strain gauges were applied on the specimens to measure the strain. Four specimens of each composition were tested. After tensile fracture, the fracture surfaces were examined under a scanning electron microscope (SEM).

### RESULTS AND DISCUSSION

The results on both the electrical and mechanical properties of all composites are shown in Tables 2 and 3, respectively, as discussed below.

Fig. 2 shows the variation of the electrical resistivity

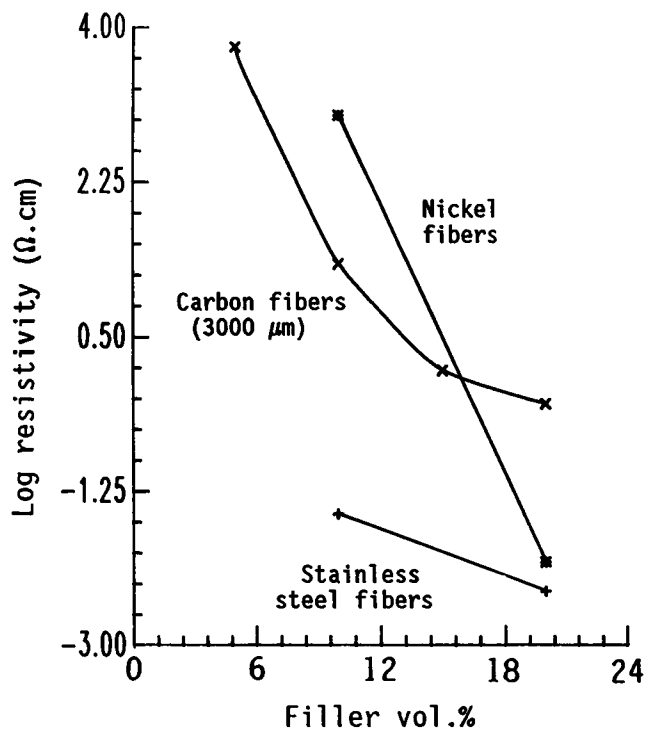


Fig. 2 Variation of the electrical resistivity with filler volume fraction for carbon (3000 μm), nickel and stainless steel fibres up to 20 vol%

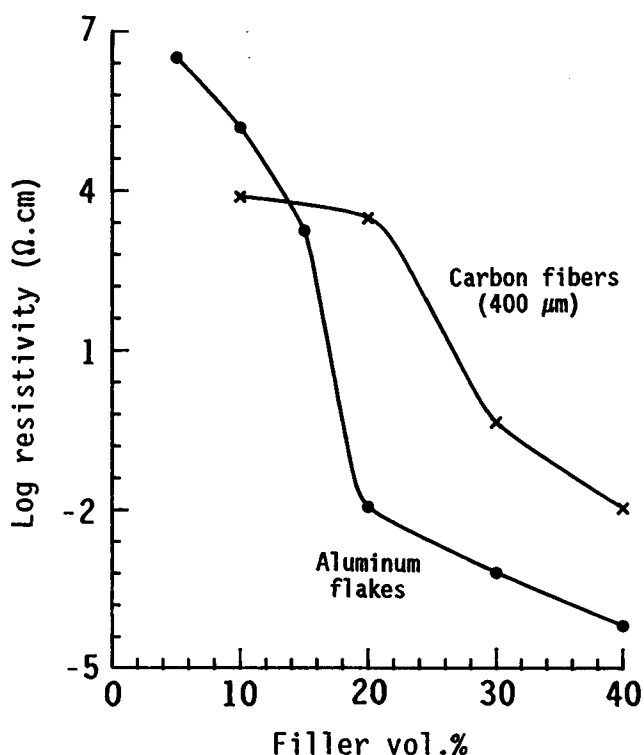


Fig. 3 Variation of the electrical resistivity with filler volume fraction for carbon fibres (400 μm) and aluminium flakes up to 40 vol%

with filler volume fraction for carbon (3000 μm), nickel and stainless steel fibres up to 20 vol%. The resistivity was lowest for the stainless steel fibres. It was higher for the nickel fibres than the carbon fibres at 10 vol%, but

was lower for the nickel fibres than the carbon fibres at 20 vol%. Fig. 3 shows the variation of the resistivity with filler volume fraction for carbon fibres (400 μm) and aluminium flakes up to 40 vol%. The resistivity was higher for the aluminium flakes than the carbon fibres at 10 vol%, but was lower for the aluminium flakes than the carbon fibres at ≥ 20 vol%.

Table 4 shows the measured and calculated resistivity of the Al flake composite. Two methods (Equations (1) and (3)) were used to calculate the resistivity. Equation (3) gave calculated values that were closer to the measured values. The ratio of the measured resistivity to either calculated value decreased sharply with increasing Al flake volume fraction. This is because a higher Al flake volume fraction allowed the flakes to be in more intimate contact, thereby decreasing the resistance at the contact between adjacent Al flakes.

Table 5 shows the measured and calculated resistivity of the carbon fibre (400 μm) composites. The calculated resistivity was again obtained using Equations (1) and (3), with Equation (3) giving values closer to the measured values than Equation (1). The ratio of the measured resistivity to either calculated value decreased sharply with increasing fibre volume fraction.

An oxide was absent on the carbon fibres and present on the Al flakes. The aluminium oxide, being electrically insulating, increased the resistance at the contacts between adjacent Al flakes. In spite of this, the measured resistivity was much higher for the carbon fibre composites than the Al flake composites of the same filler volume fraction ≥ 20 vol%. This is due to the higher resistivity of the carbon fibres ( $3 \times 10^{-3} \Omega \text{ cm}$ ) compared with the Al flakes ( $2.65 \times 10^{-6} \Omega \text{ cm}$ ) by themselves.

From the above discussion, it can be found that the calculated values based on Equation (3) are closer to the measured values than those based on Equation (1), especially when the volume fraction of the conducting filler is higher than the required critical volume fraction. This is mainly because the assumptions behind Equation (3) are closely satisfied by the composites of this investigation. However, differences between the measured values and the calculated values (Equation (3)) remain. This difference may be attributed to the fact that Equation (3) does not take into account any dimensional aspect of the fibres in the matrix. Because some of the fibres may not contribute to network formation, not all the fibres may be electrically effective in conductive path formation, even if they are oriented in the direction of the electric field.

Table 6 shows the measured and calculated values of the critical filler volume fraction for electrical conduction. The measured values were obtained from Table 2. The calculated values were based on a model<sup>13</sup> that takes into account the filler geometry. The agreement between the measured and calculated values is quite good, especially for fillers with low aspect ratios. For fillers of high aspect ratios, such as carbon fibres of length 800 or 3000 μm, the discrepancy between the measured and calculated critical volume fractions is due to the tendency for the long fibres to be curved.

Table 7 shows the EMI shielding effectiveness at 1.5 GHz for PES composites containing various fillers at 20 vol%.

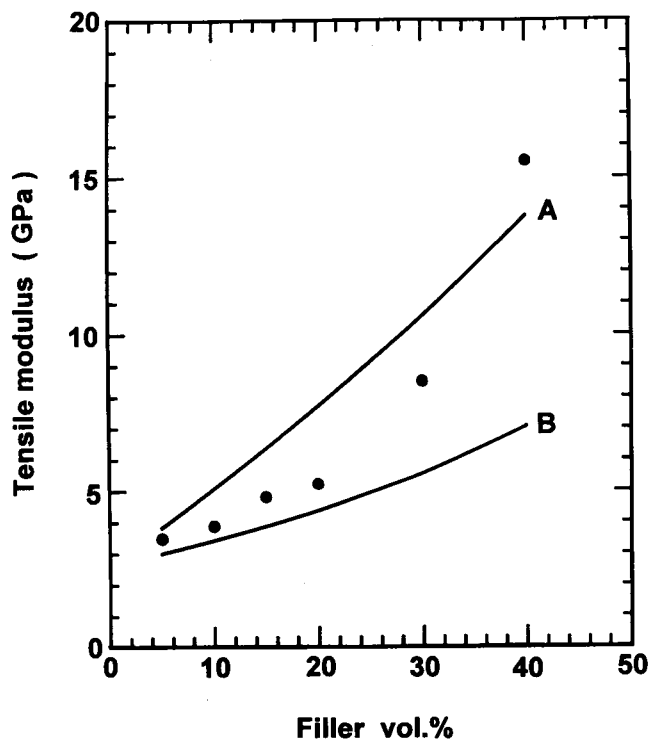


Fig. 4 Variation of the tensile modulus with filler volume fraction for composites containing Al flakes: A, short fibre composite model; B, particulate composite model; ●, experimental results

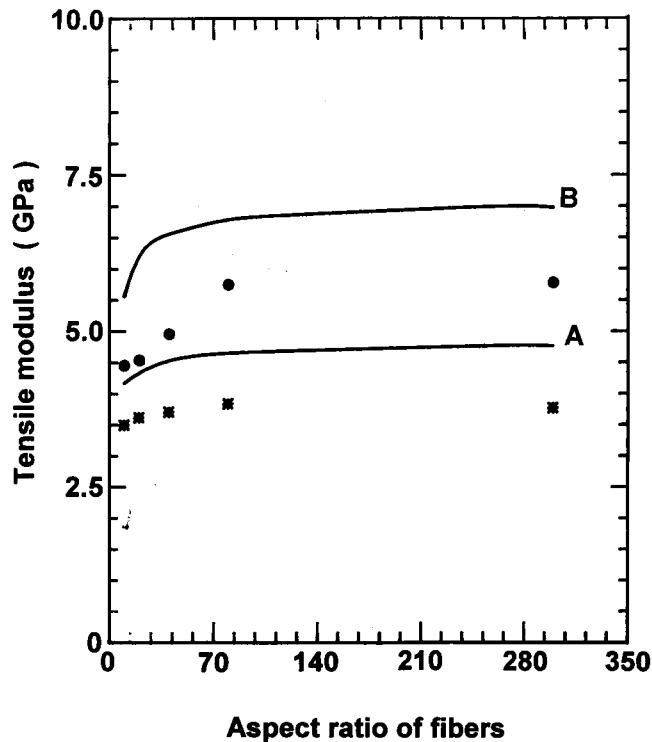


Fig. 6 Variation of the tensile modulus with fibre aspect ratio for composites containing 10 vol% (A) and 20 vol% (B) carbon fibres. \* and ● are experimental results corresponding to the calculated curves A and B, respectively

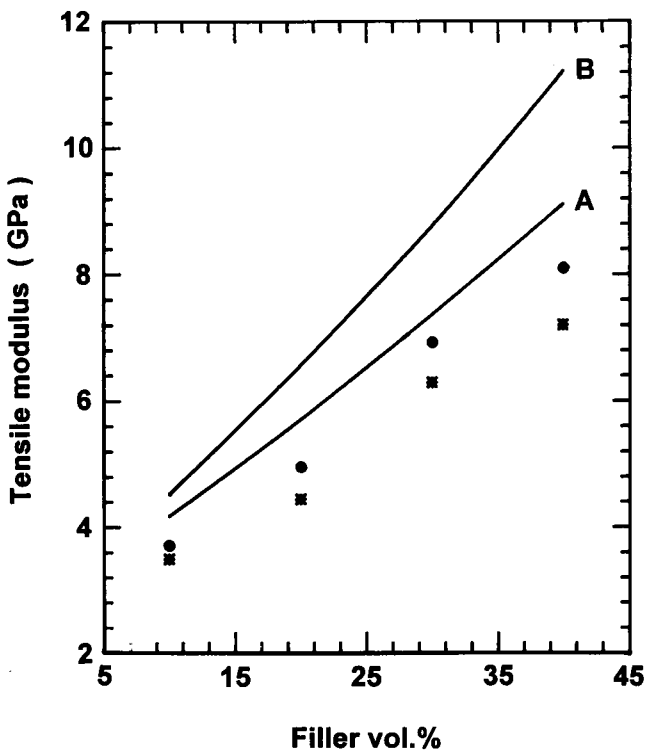


Fig. 5 Variation of the tensile modulus with filler volume fraction for composites containing carbon fibres (100 and 400  $\mu\text{m}$  long). Theoretical data: A, aspect ratio 10; B, aspect ratio 40. Experimental results: \*, aspect ratio 10; ●, aspect ratio 40

to a typically large ( $> 10$ ) aspect ratio for a fibre. A flake has two aspect ratios. One is the length over the thickness; the other is the width over the thickness. For the

**Table 8. Minimum filler volume fraction for EMI shielding effectiveness  $> 50$  dB**

Filler	Volume fraction (%)
Carbon fibres (200, 400 $\mu\text{m}$ )	40
Ni fibres	20
Stainless steel fibres	20
Al flakes	30

flakes used in this work, they are 40 and 33, respectively. The model for particle-filled composites does not consider the aspect ratio at all. However, in the model for short fibre composites, only one aspect ratio is considered. Therefore, the experimental results are in between the calculated values based on these two models. It is not clear why the modulus of the composite containing 40 vol% Al flakes is higher than the calculated value obtained using the short fibre composite model.

Fig. 5 shows the variation of the tensile modulus with volume fraction (up to 40%) for composites containing short carbon fibres. Curves A and B are theoretical data for the aspect ratios 10 and 40, respectively. In contrast to the Al flake composites, the measured modulus values of short carbon fibre (100 and 400  $\mu\text{m}$  long) composites fall on a curve having the same shape as, but lower than, the corresponding theoretical curve based on the short fibre composite model (Equation (7)). Fig. 6 shows the

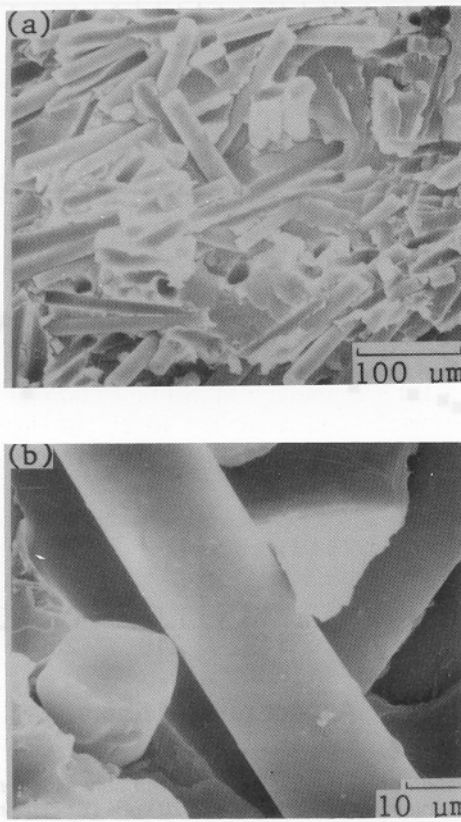


Fig. 7 SEM photographs of the tensile fracture surface of a composite containing 20 vol% carbon fibres (400 µm)

variation of the tensile modulus with fibre aspect ratio for composites containing 10 and 20 vol% short carbon fibres. Curves A and B are calculated results based on the short fibre composite model (Equation (7)) for 10 and 20 vol% short fibres, respectively. The experimental results for each volume fraction are lower than the corresponding calculated ones. That the measured modulus values are lower than the calculated values in both Figs 5 and 6 may be attributed to the fact that the fibres are not straight in the composites. The curved morphology of the fibres may be a reason for the low measured modulus of the composites. Because some of the fibres may contribute to conduction in the direction normal to the plane of the sample, the ideal planar isotropic behaviour of the composites may be disrupted, thus resulting in a difference between the measured and calculated results. The weak bonding between the fibres and the matrix may also contribute to the difference.

Table 8 shows the minimum filler volume fraction for the EMI shielding effectiveness to be  $> 50$  dB. Although Ni and steel fibres required the least filler (20 vol%) to achieve this, the mechanical properties were relatively poor at this filler volume fraction for these fillers.

The relatively poor mechanical properties of the carbon fibre composites is due to the poor bonding between the carbon fibres and the PES matrix, as indicated by the fibre pull-out observed on the tensile fracture surface (Fig. 7, 20 vol% carbon fibres (400 µm)). Similar fracture surface examination of PES containing 20 vol% Ni fibres revealed even more fibre pull-out. This means that the bonding between the filler and the PES matrix was even

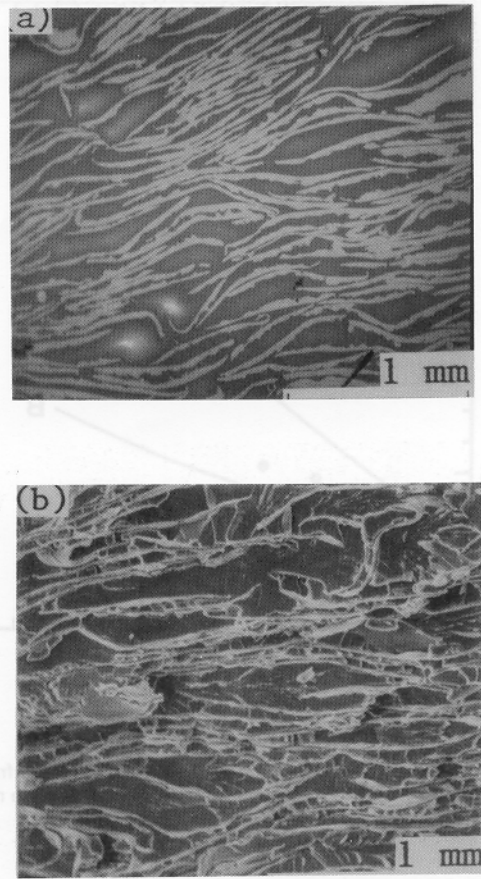


Fig. 8 SEM photographs of 40 vol% Al-flake-filled PES composites: (a) polished surface; (b) tensile fracture surface

worse for Ni fibres. This is why the mechanical properties were correspondingly lower for the Ni fibre composites.

The relatively good mechanical properties of the Al flake composites is due to the good bonding between the Al flakes and the PES matrix, as indicated by the lack of flake pull-out in the fracture surface (Fig. 8(b)). A micrograph of the polished surface of this composite (40 vol% Al flakes) is shown in Fig. 8(a). Both Figs 8(a) and 8(b) show that the Al flakes are preferentially aligned.

The good bonding between the Al flakes and the PES matrix is partly due to the fact that each Al flake (fabricated by rapid solidification) had one smooth side and one rough side, as shown in Fig. 9. Fig. 9(a) shows a few Al flakes — some with the smooth side upwards and others with the rough side upwards. Fig. 9(b) is a higher magnification photograph showing part of the rough side of a single Al flake. The oxide on the Al flakes may also help the bonding between the flakes and the PES matrix.

Table 9 shows the resistivity of PES containing 40 vol% Al flakes before and after heating in air at  $140 \pm 5^\circ\text{C}$  for up to 144 h. The heating had essentially no effect on the resistivity. The stability of the Al flake composites at  $140^\circ\text{C}$  makes them of practical importance to automobile applications. It can be concluded that the composite having the best combination of electrical and mechanical properties was PES containing 40 vol% Al flakes.

The tensile strength of Al flake/PES (65.1 MPa at 33.0

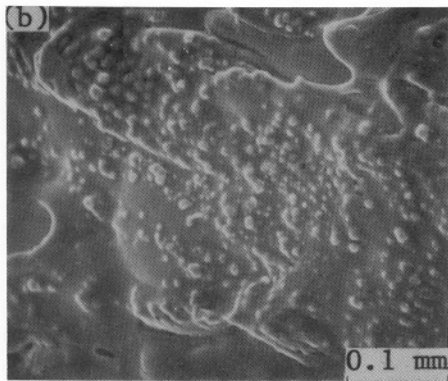
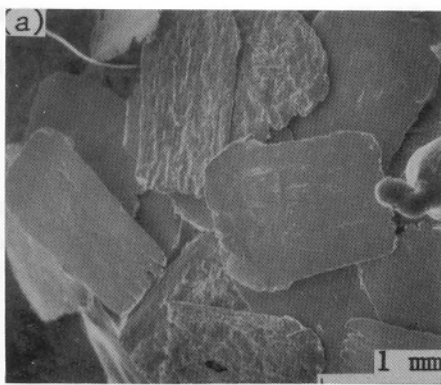


Fig. 9 SEM photographs of Al flakes. (a) Both sides (smooth and rough) of Al flakes; (b) higher magnification of the rough side of a single Al flake

**Table 9. Electrical resistivity of PES containing 40 vol% aluminium flakes before and after heating in air at  $140 \pm 5^\circ\text{C}$  for various lengths of time**

Time (h)	Resistivity ( $10^{-5} \Omega \text{ cm}$ )	
	Before	After
24	$9.27 \pm 0.42$	$10.10 \pm 0.12$
48	$8.56 \pm 1.02$	$7.99 \pm 0.02$
99	$7.93 \pm 1.08$	$8.48 \pm 1.35$
144	$6.41 \pm 0.76$	$6.45 \pm 0.10$

weight% (wt%) or 20 vol%, and 65.9 MPa at 45.75 wt% or 30 vol% Al flakes) is comparable to that of Al flake/nylon 6,6 (65.5 MPa at 40 wt% Al flakes<sup>3</sup>, 62.06 MPa at 40 wt% Al flakes<sup>1</sup>), higher than that of Al flake/polycarbonate (44.1 MPa at 40 wt% Al flakes<sup>3</sup>, 42.75 MPa at 40 wt% Al flakes<sup>1</sup>), higher than that of Al flake/SMA copolymer (44.82 MPa at 40 wt% Al flakes<sup>1</sup>) and much higher than that of Al flake/PVC<sup>5</sup>.

The electrical resistivity of Al flake/PES ( $6.6 \times 10^{-4} \Omega \text{ m}$  at 45.75 wt% or 30 vol% Al flakes,  $1.2 \times 10^{-2} \Omega \text{ cm}$  at 33.0 wt% or 20 vol% Al flakes) is lower than those of Al flake/PVC ( $4.0 \times 10^{-2} \Omega \text{ cm}$  at 40 wt% Al flakes<sup>5</sup>), Al flake/nylon 6,6 ( $1.0 \Omega \text{ cm}$  at 40 wt% Al flakes<sup>1</sup>,  $10^2 \Omega \text{ cm}$  at 40 wt% Al flakes<sup>3</sup>), Al flake/SMA copolymer ( $1.0 \Omega \text{ cm}$  at 40 wt% Al flakes<sup>1</sup>) and Al flake/polycarbonate ( $1.0$

$\Omega \text{ cm}$  at 40 wt% Al flakes<sup>1</sup>,  $10 \Omega \text{ cm}$  at 40 wt% Al flakes<sup>3</sup>).

Among the polymers (other than PES) mentioned above, only PVC gives an Al flake composite of resistivity that is as low as  $10^{-2} \Omega \text{ cm}$ , but the mechanical properties are poor for Al flake/PVC<sup>5</sup>. Therefore, Al flake/PES is superior to the other Al flake/polymer-matrix composites in its combination of good electrical and mechanical properties.

## CONCLUSIONS

Carbon, nickel and stainless steel fibres and aluminium flakes were used as fillers in PES to obtain electrically conducting composites. The filler/matrix bonding was strongest for the aluminium flakes, intermediate for the carbon fibres and weakest for the metal fibres. As a result, the tensile strength of the composites degraded when the filler volume fraction exceeded 10% for the metal fibres, 30% for the carbon fibres (of length 200 or 400  $\mu\text{m}$ ), and  $> 40\%$  for carbon fibres (of length 100  $\mu\text{m}$ ) and aluminium flakes. On the other hand, an EMI shielding effectiveness exceeding 50 dB required 20 vol% of metal fibres, 30 vol% of aluminium flakes, or 40 vol% of carbon fibres (of length 200 or 400  $\mu\text{m}$ ). Thus, even though the metal fibres were most effective for EMI shielding, they were least effective for strengthening the composite. Aluminium flakes at 40 vol% gave the best combination of electrical and mechanical properties. The resistivity was  $6.6 \times 10^{-5} \Omega \text{ cm}$  and the tensile strength of 67 MPa was the highest among all the composites investigated. Furthermore, the resistivity was not affected by heating in air at  $140 \pm 5^\circ\text{C}$  for up to at least 144 h. These properties, together with the low cost of aluminium flakes, make aluminium-flake-filled PES attractive for EMI shielding, die attach and other applications in electronic packaging.

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## REFERENCES

- 1 Nangrani, K. and Gerteisen, S. *Research & Development* (July 1985) p 60
- 2 Ward, S., Bolvari, A. and Gorry, B. *Proc 4th Int SAMPE Electronic Materials & Processing Conf (Electronic Materials—Our Future)* edited by R. E. Allred, J. Martinez and K. B. Wischmann (SAMPE, Covina, CA, USA, 1990)
- 3 Crosby, J.M. and Travis, J.E. *Rubber World* **193** No 2 (1985) pp 30–33
- 4 Li, L. and Chung, D.D.L. *Proc 4th Int SAMPE Electronic Materials & Processing Conf* op. cit. pp 777–785
- 5 Kleiner, L.W. and Pazur, A.S. *J Vinyl Technol* **4** No 4 (1982) pp 157–159



- 6 **Blythe, A.R.** *Electrical Properties of Polymers* (Cambridge University Press, 1980) p 126
- 7 **Christensen, R.M.** *Mechanics of Composite Materials* (Wiley-Interscience, New York, 1979) p 129
- 8 **Whitney, J.M., Daniel, I.M and Pipes, R.B.** *Experimental Mechanics of Fiber Reinforced Composite Materials* (The Society for Experimental Stress Analysis, 1982)
- 9 **Hashin, Z.** 'Theory of composite materials' *Mechanics of Composite Materials* edited by F.W. Wendt, H. Liebowitz and N. Perrone (1970) p 201-242
- 10 **Halpin, J.C. and Kardos, J.L.** *Polym Engng Sci* **16** No 5 (1976) p 344
- 11 **Abrate, S.** *Rubber Chem Technol* **59** (1986) p 384

- 12 **Mallick, P.K.** *Fiber-Reinforced Composites* (Marcel Dekker, New York, 1988) p 110
- 13 **Milewski, J.V.** *Ind Eng Chem Prod Res Dev* **17** (1978) pp 363-366

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