Effect of moisture absorption and fiber orientation on electrical conductivity and electromagnetic interference shielding of carbon fiber reinforced bioplastic composites

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Received 15 October 2018

Revised 16 January 2019

Accepted 21 January 2019

Published 5 March 2019

The aim of this study is to discuss the effect of moisture absorption on electrical conductivity and electromagnetic interference of the carbon fiber (CF) reinforced bioplastic composite. The composites were prepared by the hot press machine, and immersed in water for 20 and 40 days. The electrical conductivity measurements were carried out as a function immersed time. The electrical conductivity of CF with two layers is greater than that of one layer, because the electrical conductivity increases with increasing the volume filler of CF. The electrical conductivity slightly increases with increasing the immersion time. The EMI SE (electromagnetic interference shielding effectiveness) of the composite was examined with the frequency from 500 MHz to 2000 MHz. The EMI SE of the CF increases with increasing the content of the CF, and the EMI SE result of composite is around 50 dB to 60 dB. There is scarcely significant effect of orientation on composite on the EMI SE.

Keywords: Carbon fiber; bioplastic; EMI; electrical conductivity; moisture effect.

PACS number: 61.41.+e

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1. Introduction

Electromagnetic interference (EMI) shielding has been widely used in many applications such as mobile telecommunications, radar, Wi-Fi, television, computer and electronic devices, etc.¹ The main mechanism is how the material shields such devices from the penetration of the radiation. The EMI shielding effectiveness increases with increasing the conductivity. Therefore, the materials with high conductivity are metal, copper, aluminum, carbon fiber, etc.^{2,3} Because the EMI leads to affect organism by electronic devices, the applications such as commercial, military and electronic equipment should keep away from EMI. The preparation of EMI shielding materials should give serious attention. There have limits of properties of EMI shielding mechanism such as heavy weight, corrosion, and low process ability. Thus, EMI should draw back to reduce the utilization problems for future applications.⁴

The carbon fiber (CF) is the best electrically conductive material, because the CF has the great properties of electrical and heat conduction. Therefore, if the polymer matrix will need conductive and electrical properties, the CFs should be blended. Because the CF has better mechanical, physical and thermal properties, the CF is used as reinforce filler.⁵ Bioplastic polymer has been widely used for many applications, especially in food packaging. The ecoflex is bio-based polymer. Because it is made from renewable sources such as corn starch, the disadvantage of the ecoflex is low mechanical properties and the easy water absorption. Therefore, the ecoflex is combined with poly lactic acid (PLA) and CaCO_3 to improve the properties of bioplastic. PLA plastic can solve the pollution issue affected by chemicals. Therefore, developing of renewable resources polymer based on PLA is a right choice and promising.⁶ Then, the combination of the ecoflex and PLA results in good mechanical properties. Lot of literature sources and publications indicate how to improve the mechanical properties of bioplastic. In this study, the CF with good mechanical and electrical conductivity properties is used as reinforcing phase of bioplastic matrix. But, it trends for the bioplastic composite to absorb the water easily. It is very important to discuss the effect of moisture on electrical conductivity of bioplastic composite. Furthermore, when the fiber orientation is changed, though the mechanical properties depends on the fiber orientation, there are a few studies for the effect of fiber orientation on electromagnetic interference shielding effectiveness EMI SE of bioplastic composite.

2. Experimental Procedure

2.1. Materials

A PAN carbon fiber yarn (Toho Tenax, Japan) consisting of 24,000 filaments (diameter size ~ 6 μm , density 1.8 g/cm^3 , tensile strength 4900 MPa, Young's modulus 230 GPa) was used as reinforcements. Bioplastic was supplied in sheet

with thickness 0.1 ± 0.01 mm by Japan Industries, LLC. Two kinds of bioplastic were used as matrix, which consists of 10% of PLA, 80% of ecoflex c1200, and 10% of CaCO_3 (BPM 10), and 45% of PLA, 45% of ecoflex c1200, and 10% of CaCO_3 (BPM 45). The thermal properties of bioplastic have a glass transition temperature (T_g) of 50°C to 60°C , and a melting temperature (T_m) of 110°C to 125°C .

2.2. Sample preparation of CF reinforced bioplastic composite

The composites were produced by using film-stacking method followed by hot pressing at processing temperatures of 120°C to 130°C , with the thickness of 0.6 mm to 0.8 mm. The applied pressure was 3 MPa to 4 MPa for holding time after 90 s, as shown in Fig. 1. The reinforcing of CF layers was placed on each other in unidirectional 90° and $45/90^\circ$ orientation. The plate packages were inserted between the preheated plates and held without applying pressure for 30 s. When the lamination of composite put into plates, the plates were pressed by 3 MPa for 90 s and then

Fig. 1. Processing diagram of the hot pressing of CF-BPM composites.

The lamination of composite A and B

The lamination of composite C and D

Fig. 2. The detail of composites A, B, C and D.

cooled down. The composites were immersed in normal water (distilled water) for 20 and 40 days and then measured the electrical conductivity. Figure 2 shows the film-stacking composition of the bioplastic and reinforcements of CF. Four types of composite were produced from these preparation;

- (1) Composite A: one layer of CF and two layers of BPM 10,
- (2) Composite B: one layer of CF and two layers of BPM 45,
- (3) Composite C: two layer of CF and three layers of BPM 10,
- (4) Composite D: two layer of CF and three layers of BPM 45.

2.3. Electrical conductivity

The electrical conductivity of the CF reinforced bioplastic composites with unidirectional 90° orientations was measured by using instrument on Keithlink, probing (Keithlink technology. Co. Ltd) which is measured with two probes method at room-temperature according to ASTM D4496-13. Samples are trimmed into 3 × 3 cm section. At least five specimens for each sample have been used to obtain nominal average results. The probe needle was attached and used to contact the surface of specimen which was coated by the conductance materials such as metal to obtain the electrodes. The conductive link between the sample and the clamps of the instrument passed constant current through the composite. The electrical conductivity was calculated by the following equation;

$$\sigma = \frac{L}{AR}, \quad (1)$$

where σ is the electrical conductivity through the thickness of the sample (S/cm), L the length of the sample in the measurement direction (cm), R the electrical resistance (ohm), and A the cross-sectional area (cm²).^{8,9,20} After two immersion times of 20 and 40 days, the samples were carefully wiped off with the tissue paper and allowed to reach to laboratory temperature before measuring the electrical conductivity and their weight with an analytical balance having a resolution of 0.0001 g. The length of sample was measured with a digital Vernier caliper with 0.01 mm least count, whereas width and thickness dimensions were measured using a digital micrometer to three digits' precision. The weight and dimensions swelling of samples were immediately calculated.

2.4. Electromagnetic interference shielding effectiveness (EMI SE)

The shielding effectiveness (SE) is an important parameter to consider the shielding properties of materials.² The standard used to measure the SE is ASTM D4935. The SE was evaluated by frequency range from 500 MHz to 2 GHz and calculated by the following equation.¹⁰ In the measurements, a network analyzer (ZVRE Rohde & Schwarz) was used as a signal generator and receiver. The EMI shielding of composite was measured in Taiwan Textile Research Institute (TTRI). Physical dimensions of the specimen holder are given in the

standard

$$SE = 10 \log[Pi/Po] = 20 \log[Ei/Eo], \quad (2)$$

where Pi is the incident energy, Ei the incident electric intensity, Po the transmitted energy and Eo the transmitted electric intensity.

3. Results and Discussion

3.1. Electrical properties of CF reinforced bioplastic composite

The results of resistance and electrical conductivity of the CF reinforced bioplastic composites with unidirectional 90° orientation are shown in Table 1. The resistivity and the conductivity are a reciprocal relation. Therefore, the materials, which have high resistivity, will have low conductivity. The electrical conductivity of the CF with one layer and two layers are 1.9 and 2.3 S/cm, respectively. The electrical conductivity of the CF with two layers is greater than that of one layer, because the electrical conductivity depends on the volume of CF. Therefore, the CF contributes to enhance the conductivity of the composite.¹¹ The electrical conductivity of composites A, B, C, and D is less than that of the CF, because the bioplastic is nonconductive materials. Thus, the composite strongly reduces the electrical conductivity.

The effect of moisture absorption on the electrical conductivity of the CF reinforced bioplastic composite is also shown in Table 1. When the immersion time increased from 0 day to 40 days, the weight of samples increased, regardless of composites A-B. This indicates that the moisture content increases with increasing the immersion time.

The electrical conductivity of the composites A, B, C and D, increases also with increasing the immersion time. This results from the moisture absorption of the composite. Kumar *et al.*¹² have reported that the moisture absorption increases the effective conductivity of the sample. Wang *et al.*¹³ indicated that water as a source of hydrogen affects the physical and chemical properties of minerals. They have explained that the electrical conductivity is strongly dependent on water content. It is proposed that water content of hydrogen source enhances the electrical conductivity which is charged by protons and is indirectly enhancing the ionic conductivity. Jafar *et al.*¹¹ explained that the electrical conductivity ($\sigma(\omega)$) increases with increasing weight gain (M%) due to water absorption. It has found that dielectric constant increases when the percentage of moisture absorption increases, whereas dielectric constant (ϵ) is dependent on capacity of composite materials. Water has low electrical properties, which increases significantly with increasing salvation of a small amount of ionic element such as hydrogen.¹³⁻¹⁵ The increase in water absorption results in the increase in the electrical conductivity of the composites. These results show that the conductivity of the composite depends on absorbed water. It is clear that when the sample of the composite immerses in water for long period the water content would affect the electrical conductivity of the composite.

Table 1. The variation of electrical resistant and conductivity when immersion time changed from 0 day to 40 days.

Sample Code	Length (cm)	Width (cm)	Thickness (cm)	Weight (mg)	Resistance (Ω)	Resistivity ($\Omega \cdot \text{cm}$)	Conductivity ($\text{S} \cdot \text{cm}^{-1}$)
CF-1 layer	2.97	2.84	0.03	1.4	$1.76, 10^{-3}$	$5.0, 10^{-5}$	$1.9, 10^4$
CF-2 layers	2.99	2.81	0.04	2.6	$1.02, 10^{-3}$	$4.3, 10^{-5}$	$2.3, 10^4$
Composite A-0	2.97	2.84	0.03	3.7	$2.41, 10^4$	$6.9, 10^2$	$14, 10^{-4}$
Composite A-20	2.75	2.99	0.03	4.1	$1.11, 10^4$	$3.6, 10^2$	$27, 10^{-4}$
Composite A-40	2.93	2.77	0.03	4.4	$1.05, 10^4$	$2.9, 10^2$	$33, 10^{-4}$
Composite B-0	2.93	2.82	0.03	3.9	$2.14, 10^4$	$6.1, 10^2$	$16, 10^{-4}$
Composite B-20	3.04	2.69	0.03	4.01	$1.85, 10^4$	$4.9, 10^2$	$20, 10^{-4}$
Composite B-40	3.02	2.73	0.03	4.2	$1.29, 10^4$	$3.4, 10^2$	$28, 10^{-4}$
Composite C-0	2.99	2.84	0.05	3.6	$2.20, 10^4$	$10.5, 10^2$	$9.4, 10^{-4}$
Composite C-20	2.97	2.81	0.05	3.9	$1.30, 10^4$	$6.1, 10^2$	$16, 10^{-4}$
Composite C-40	3.04	2.77	0.05	4.2	$1.2, 10^4$	$5.4, 10^2$	$18, 10^{-4}$
Composite D-0	2.99	2.84	0.05	3.8	$2.39, 10^4$	$11.3, 10^2$	$8.8, 10^{-4}$
Composite D-20	3.02	2.93	0.05	4.2	$2.09, 10^4$	$10.1, 10^2$	$9.8, 10^{-4}$
Composite D-40	3.04	2.87	0.05	4.6	$1.22, 10^4$	$5.7, 10^2$	$17, 10^{-4}$

Fig. 3. (Color online) EMI SE as function of frequency from 500 MHz to 2000 MHz range on bioplastic, CF, composites C and D.

Table 2. EMI SE data of bio plastic, CF, and composite.

Samples	EMI SE (dB)			
	500 MHz	1000 MHz	1500 MHz	1900 MHz
Bio Plastic	0.05	0.12	0.18	1.12
CF-1 layer	51.70	48.34	48.14	49.33
CF-2 layer	60.09	61.18	62.70	67.84
Composite C-Unidirectional 90°	68.31	59.49	60.18	68.44
Composite C-45/90°	66.29	59.88	59.66	67.16
Composite D-Unidirectional 90°	68.01	59.74	60.13	64.78
Composite D-45/90°	68.45	59.59	60.11	63.21

3.2. EMI shielding of carbon fiber reinforced bioplastic composites

An electromagnetic wave was directly injected into the composite using waveguide based on ASTM D4935. The frequency was scanned from 500 MHz to 2000 MHz. These frequencies are normally produced by the usual pieces of equipment like mobile phones, microwave ovens, bluetooth, wireless telephones, etc. Two levels of electromagnetic field and shielding can be distinguished, as follows;

- Professional level/High absorbed the EMI: > 30 dB
- General level/Low absorbed the EMI: < 30 dB

The EMI shielding results are shown in Fig. 3 and Table 2. It is clear that the EMI SE of the bioplastic is 0.05 to 1.12 dB under frequency range of 500 MHz to 2000 MHz. The bioplastic cannot absorb the electromagnetic interference. The

EMI SE of the composite is indicated by the reflection loss and the absorption loss and can be influenced by their electrical conductivity.⁷ If the materials would be highly electrical conductivity, the materials tend to reflect the electromagnetic wave.

Therefore, the CF reinforced bioplastic composite has high the EMI SE. When the EMI SE of the CF between one layer and two layers compares, the EMI SE of the CF with two layers is greater than that of the CF with one layer. Ayesha Kausar *et al.* observed that the EMI increases with increasing the content of the CF.¹⁷ The increase in the EMI SE results from the content of the CF because the formation of more networks of conductive filler and the large source of free electrons in the material can interact with incoming electromagnetic wave.¹⁷

The EMI SE of the composites C and D is 68.4 and 64.8 dB, respectively. The EMI SE of the composite C is slightly greater than that of the composite D. This may result from increasing the content of PLA in composite. Because the composites C and D show the EMI SE above > 60 dB, the composites C and D show good electromagnetic wave interference. Figure 3 shows also the effect of the orientation of the composite on the EMI SE. The EMI SE of the composite with unidirectional orientation of 90° is almost the same as the orientation of 45/90°, regardless of the composites C and D. This suggests that because the unidirectional 90° of the CF contributes uniformly to conductive network in blend matrix which interacts with the electromagnetic waves,¹⁸ there is scarcely the effect of fiber orientation on the electrical conductivity. Jagatheesan *et al.*¹⁹ observed the same as this results which the weave has no significant effect on the EMI SE.

4. Conclusion

The effect of moisture absorption and the CF orientation on electrical conductivity and electromagnetic interference of the CF reinforced bioplastic composite have been studied. The electrical conductivity of the CF of two layers was greater than that of one layer of the CF. When the immersion time increased, the electrical conductivity of the bioplastic composite increased. The EMI SE of the CF increased with increasing the content of the carbon fiber. The effect of orientation of composite on the EMI SE was scarcely observed for the composite, because the EMI SE of unidirectional orientation 90° was almost the same as that of orientation 45/90°, regardless composites C and D. The last conclusion of this study has shown that the CF reinforced bioplastic composites can be promising materials for the EMI shielding availability.

References

1. L. Q. Chen *et al.*, *Carbon* **95**, 10 (2015).
2. C. S. Zhang *et al.*, *Compos. Sci. Technol.* **67**, 2973 (2007).
3. S. Y. Yang *et al.*, *Compos. Appl. Sci. Manufact.* **36**, 691 (2005).
4. F. Wu *et al.*, *Rsc Adv.* **4**, 38797 (2014).

5. M. F. Jing *et al.*, *Rsc Adv.* **6**, 100090 (2016).
6. E. Elena, *Sci. Bull. Ser. F. Biotechnol.* **18**, 2014 (2014).
7. C.-T. Hsieh *et al.*, *Fibers Polym.* **17**(4), 615 (2016).
8. N. Likittanaprasong, M. Seadan and S. Suttiruengwong, *IOP Conf. Ser. Mater. Sci.* **41** *Eng. Materials Science and Engineering* 87 (2015).
9. N. Li *et al.*, *Nano Letters* **6**(6), 1141 (2006).
10. Alberto Lopez Caro, *Thesis. Czech Technical University, Prague*, (2011).
11. H. I. Jafar, S. I. Husaen and E. A. Al-Ajaj, *J. Al-Nahrain Univ.* **14**(4), 87 (2011).
12. M. Zulfequar and A. Kumar, *Rev. Phys. Appl.* **21**, 525 (1986).
13. D. Wang *et al.*, *Nature* **443**, 977 (2006).
14. Y. Shiji, *Conf. Elect. Insul. Dielectric Phenomena* (2004).
15. I. L. Hosier, *Annual Report Conference on Electrical Insulation and Dielectric Phenomena* (2014).
16. Katalin, *Obuda University e-Bulletin*, 2016 (2011).
17. A. Kausar, *Int. J. Mater. Chem.* **6**(1), 6 (2016).
18. M. Arjmand *et al.*, *Carbon* **49**, 3430 (2011).
19. K. Jagatheesan, *Indian J. Fibre Textile Res.* **39**, 329 (2014).
20. WS. Sipahutar, *Thesis, National Taiwan University of Science and Technology, Taipei*, (2017).