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Needle-Bonded Electromagnetic Shielding Thermally Insulating Nonwoven Composite Boards: Property Evaluations

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Abstract: Complicated environmental problems inevitably arise when technology advances. One major environmental problem is the presence of electromagnetic radiation. Long-term exposure to electromagnetic radiation can damage people's health in many ways. Therefore, this study proposes producing composite boards with electromagnetic shielding effectiveness and thermal insulation by utilizing the structures and properties of materials. Different combinations of flame-retardant polyester fiber (FR fiber), recycled far-infrared polyester fiber (FI fiber), and 4D low-melting-point fibers (LM fiber) were made into flame-retardant and thermally insulating matrices. The matrices and carbon fiber (CF) woven fabric in a sandwich-structure were needle-punched in order to be tightly compact, and then circularly heat dried in order to have a heat set and reinforced structure. The test results indicate that Polyester (PET)/CF composite boards are mechanically strong and have thermal insulation and electromagnetic shielding effectiveness at a frequency between 0.6 MHz and 3 GHz.

Keywords: needle-punching; nonwoven fabrics; multilayer structure; porous materials; functional; electromagnetic shielding effectiveness

1. Introduction

Electromagnetic waves negatively influence biological systems in organisms, which has garnered intensive attention. Electronic products are continuously invented and produced for the sake of public welfare. For example, electromagnetic fields caused by mobile phones result in typical biological effects [1–3]. Some studies found that the radiation from mobile phones is surmised to be a factor in physiological changes [4–6]. It could also have a negative influence on the endocrine system, sense of hearing, metabolism, and the formation of tissues and organs [7–9]. However, the potentially beneficial effects that electromagnetic fields demonstrate on organisms are used in biomedical science to examine and explore new treatments [10,11]. On the other hand, people are also thriving to decrease and solve their adverse effects on human health and electromagnetic pollution [12–14].

Following the environmental changes, the climate also changes, and the global average temperature is rising. People thus have increasingly intense concerns about environmental protection and energy saving. As a result, the manufacturing process and materials are carefully considered in order to reduce pressure on the natural environment. Thermally insulating materials are largely used in construction in order to decrease dependence on air conditioning systems and prolong the temperature adjustment and save energy costs [15]. In order to support a minimum consumption of energy and resources, their efficient usage is needed. It will be an important measure for designs to incorporate thermally insulating materials, which facilitates energy saving and improves the thermal comfort of citizens, while enabling the construction materials to endure constantly changing outdoor weather [16].

The textile industry is the earliest developed of all industries, encompassing apparel, household fabrics, and industrial products. In particular, nonwoven fabrics have a low cost and efficient manufacturing that does not generate harmful byproducts. Nonwoven fabrics can satisfy different requirements to have innovative functions; thus, they are functional textiles that have been continuously developed and improved for different applications [17,18]. Noticeably, they have a great variety of applications, including clothes, domestic products, agricultural products, industrial products, high-tech electronic products, and aerospace industrial products [19–21].

This study combines flame-retardant polyester fiber (FR fiber), far-infrared polyester fiber (FI fiber), and low-melting-point PET fiber (LM fiber) to form flame-retardant and thermally insulating matrices. Combinations of these matrices and carbon woven fabric are then processed via needle punching and circulative heat drying, thereby forming PET composite boards and PET/carbon fiber (CF) composite boards. The mechanical properties, the limiting oxygen index (LOI), the air permeability, and the thermal conductivity of these boards are then evaluated.

2. Materials and Methods

2.1. Materials and Manufacturing

Flame-retardant polyester fiber (hereafter FR fiber) and 4D low-melting-point polyester fiber (hereafter LM fiber) were purchased from Far Eastern New Century Co., Ltd., Taipei, Taiwan). Recycled far-infrared polyester fiber (hereafter FI fiber) was purchased from True Young Co., Ltd., Tainan City, Taiwan. CF woven fabric was purchased from Toray Industries, Inc., Tokyo, Japan.

A nonwoven process was used to make two matrices: flame-retardant (FR) matrices and thermally insulating (TI) matrices. FR matrices were made of FR fibers and LM fibers at ratios of 100/0, 90/10, and 80/20, while TI matrices were made of FI fibers and LM fibers at ratios of 100/0, 90/10, and 80/20. The fibers were processed with opening, blending, carding to form webs, which were needle-punched at 200 g/m^2 and 200 needles/min at a linear speed of 1.5 m/min. The tensile force, the tearing force, and the bursting force of the matrices were evaluated, thereby determining the optimal FR and TI matrices. Two FR matrices enclosing five TI matrices were laminated and needle-punched. The multiply needle-punched composites were finally hot cured into PET composite boards using a hot circular oven. In contrast, PET/CF composite boards were made with the same manufacturing process and components as the PET composite boards, with an extra layer of CF woven fabric inserted between the top FR matrix and the first TI matrix. Figure 1 shows schematic diagrams of these two composite boards.

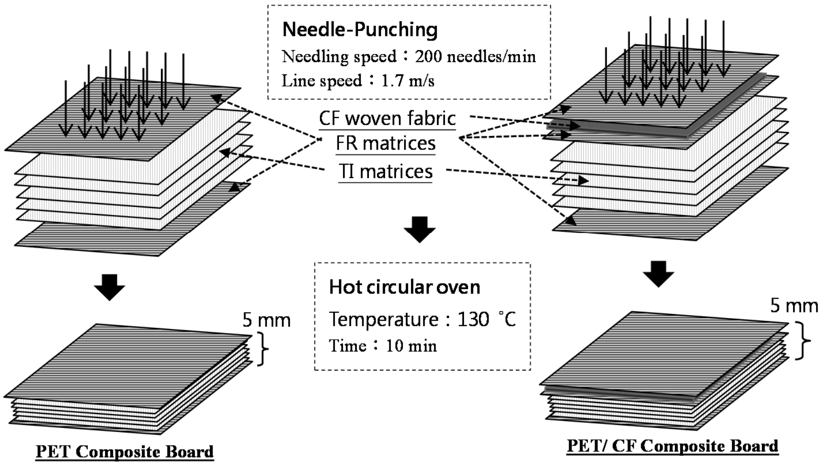

Figure 1. Illustration of composition of polyester composite boards and polyester (PET)/carbon fiber (CF) composite boards.

2.2. Testing Methods

2.2.1. Tensile Force

This test used a specified tensile speed of 300 mm/min and followed ASTM D5035-11. Ten samples of each specification were taken, samples were sized as 180 mm × 25.4 mm, and the distance between clamps was 75 mm.

2.2.2. Tearing Force

Ten samples of each specification were tested for tearing force as specified in ASTM D5035-11. The test speed was 300 mm/min, the distance between clamps was 25.4 mm, the depth of the incision was 15 mm, and samples had a size of 75 mm × 150 mm.

2.2.3. Bursting Force

The bursting force of the pure PU foam and fiber-reinforced PU foam composite boards' flame-retardant (FR) matrices and the thermally insulating (TI) matrices was conducted according to ASTM D3787-16. The samples had a size of 100 mm × 100 mm. The speed of bursting test was 100 mm/min. The circular testing head was 7 mm.

2.2.4. LOI (Limiting Oxygen Index)

A Dynisco (Atlas Technology Corp., Taipei, Taiwan) was used to measure the LOI of five samples of each specification, as specified in ASTM D2863-13. This test was conducted according to the nitrogen:oxygen ratio chart (i.e., the OI chart) of the instrument. The samples had a size of 180 mm × 25.4 mm × 5 mm. The combustion of samples was repeated until the lowest OI was yielded. The lowest OI indicates the lowest nitrogen:oxygen ratio, indicating the LOI of the sample. A high LOI indicates that samples can only be alighted in an environment in which a greater amount of oxygen is present. Namely, materials with a high LOI are highly flame-retardant.

2.2.5. Thermal Conductivity

The thermal conductivity test was performed on the PU foam and fiber-reinforced PU foam composite boards' thermally insulating (TI) matrices at 100 °C, as specified in ASTM C177-10, with a Guarded-Hot-Plate Apparatus (DRX-I-SPB, Xiangtan Huafeng Equipment Manufacture Co. Ltd., Xiangtan, China). The size of the samples was 15 cm × 15 cm × 2 cm. Three samples of each specification were tested for the mean.

2.2.6. Air Permeability

A TEXTEST (FX3300, Textest AG, Schwerzenbach, Switzerland) measures the air permeability of the PET/Kevlar thermally insulating (TI) matrices as specified in ASTM D737-04. Ten samples of each specification were taken, the sample size was 25 cm × 25 cm, and the gas pressure was 125 Pa.

2.2.7. Electromagnetic Shielding Effectiveness (EMSE)

This test followed ASTM 4935-10. The samples were evaluated for EMSE with a shielding effectiveness test fixture (E-Instrument Tech Ltd., Taoyuan, Taiwan) and a spectrum analyzer (Advantest R3132A, Burgeon Instrument Co., Ltd., Taoyuan, Taiwan). The incident frequency was between 300 kHz and 3 GHz and measured in decibels (dB).

3. Results and Discussion

3.1. Mechanical Properties of Matrices

Table 1 shows the mechanical properties along the machine direction (MD) and the cross machine direction (CD) of FR matrices and TI matrices. The optimal tensile force, tearing force, and bursting force for FR matrices occur when they are composed of a FI-to-LM ratio of 90:10. FR fiber has a high fineness, which means greater thickness and high strength. Therefore, more FR fibers provide the matrices with greater strengths. LM fiber, though it is finer, can still fill the pores formed between FR fibers and increases the overall strengths of FR matrices. However, an excessive content of 20 wt % LM fiber causes the tensile force to decrease, as more LM fiber means less FR fiber. The reinforcement primarily depends on FR fiber, and excessive LM fiber counteracts such reinforcement. Therefore, the optimal tensile force and bursting force of FR matrices (149.7 N and 507.3 N) occurs when the blending ratio is 90:10.

Table 1. Mechanical properties of far-infrared (FR) and thermally insulating (TI) matrices in relation to the fiber orientation of the machine direction (MD) and the cross machine direction (CD).

Matrices	Blending Ratio	Fiber Orientation	Tensile Force	Tearing Force	Bursting Force	LOI	Thermal Conductivity	Air Permeability
		-	N	N	N	-	W/m·K	$cm^3/cm^2/s$
FR Matrices (FR/LM)	100/0	CD MD	143.4 ± 7.93 40.2 ± 4.15	249.1 ± 19.92 141.2 ± 12.01	463.5 ± 26.24	32	-	-
	90/10	CD MD	149.7 ± 14.9 35.1 ± 4.89	226.3 ± 21.36 124.5 ± 13.78	507.3 ± 24.23	30	-	-
	80/20	CD MD	133.3 ± 8.20 36.3 ± 2.26	219.7 ± 27.73 124.5 ± 9.59	498.6 ± 33.79	29	-	-
TI Matrices (FI/LM)	100/0	CD MD	64.0 ± 6.32 26.5 ± 3.26	95.8 ± 7.85 76.3 ± 9.32	232.3 ± 21.44	-	0.033 ± 0.0081	164.2 ± 7.38
	90/10	CD MD	65.9 ± 6.55 20.3 ± 1.68	97.45 ± 8.47 81.5 ± 9.62	230.6 ± 24.34	-	0.047 ± 0.0078	152.9 ± 9.31
	80/20	CD MD	70.8 ± 5.20 23.1 ± 2.16	121.6 ± 10.91 94.5 ± 6.42	241.5 ± 23.73	-	0.045 ± 0.0166	146.7 ± 13.74

For TI matrices, the optimal tensile force, tearing force, and bursting force occur when they are composed of a FI-to-LM ratio of 80:20. FI fibers are composed of a polymer solution and a far-infrared powder, and this manufacturing process leads to a weaker fiber structure. As a result, a relatively greater amount of LM fiber (20 wt %) endows TI matrices with an optimal tensile force of 70.8 N, an optimal tearing force of 121.6 N, and an optimal bursting force of 241.5 N.

Compared with pure FR matrices (100/0), FR matrices (90/10) have a slightly lower LOI. LM fiber is not processed for its flame-retardant property, and it can be alight during combustion, which in turn affects the flame-retardant property of FR fiber. However, the LOI of FR matrices (90:10) is still 30, indicating a good flame-retardant property.

In addition, more LM fiber content results in high thermal conductivity and low air permeability in TI matrices. LM fiber has a low fineness, which means it is thin and fills the voids formed by FI fibers. Therefore, the air permeability of TI matrices decreases as a result of increasing LM fiber. Meanwhile, low air permeability in TI matrices makes ventilation difficult, thereby retaining more stagnant air. This contributes to a greater thermal insulation in TI matrices. According to the test results, FR matrices (90:10) and TI matrices (80:20) are thus selected for the sandwich-structured composite boards.

3.2. Tensile Force and Tearing Force of the PET/CF Composite Board

Figure 2a,b shows the tensile force and tearing force of the composite boards in relation to the addition of a CF woven fabric. The mechanical properties of the PET composite boards are significantly improved, in comparison to those of the FR and TI matrices. Due to the administration of multiple needle-punching, PET composite boards have fibers that are entangled along the X, Y, and Z axes and thus exhibit a significant increase in tensile force and tearing force along the CD and the MD. Furthermore, the PET/CF composite boards have greater tensile force and tearing force than do PET composite boards. The CF woven fabrics are made of carbon fiber filaments that are interwoven along the warp and weft directions perpendicularly; meanwhile, carbon fibers also contribute high strength and high modulus. Thus, CF woven fabrics can provide composite boards with higher strength than can nonwoven fabrics that are only composed of staple fibers, which are 1109.7 N along the CD for the tensile force and 1424.9 N along the CD for the tearing force.

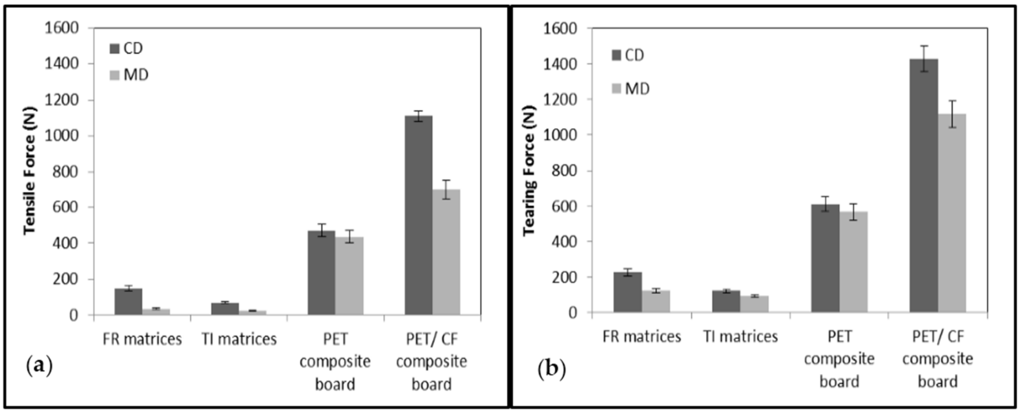

Figure 2. (**a**) Tensile force and (**b**) tearing force of the PET/CF composite boards.

3.3. The EMSE of the PET/CF Composite Boards

Figure 3a shows the EMSE of the PET/CF composite boards, while Figure 3b shows the schematic diagram of the EMSE mechanism. When electromagnetic waves are dissipated via the absorption loss and reflection loss of the surface and interior of the shielding materials, the shielding materials exhibit good EMSE. The test results indicate that the EMSE of the PET/CF composite boards is greater than that of the PET composite boards, which is ascribed to the addition of CF woven fabrics. On contacting CF woven fabrics, electromagnetic waves are absorbed and reflected by the plain weave structure and electrical properties of the CF woven fabrics, which demonstrates the EMSE of the materials. The optimal EMSE of the PET/CF composites of above 40 dB occurs when the test frequency is between 1.3 GHz and 3 GHz, indicating a shielding rate of 99.99%.

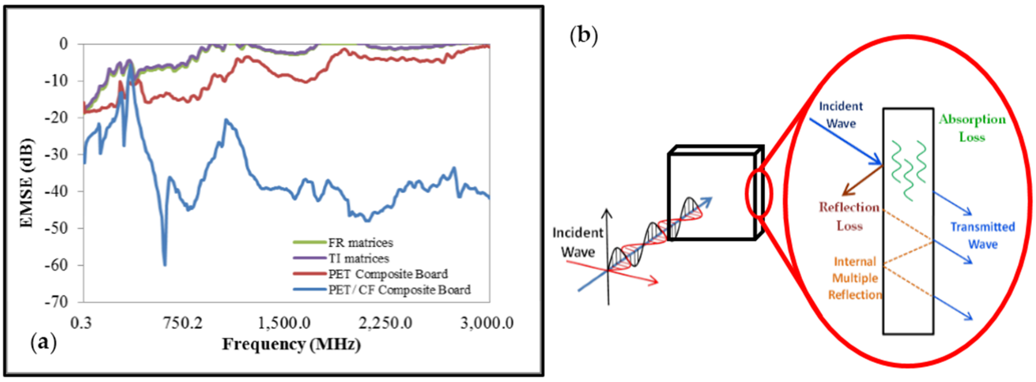

Figure 3. (**a**) Electromagnetic shielding effectiveness (EMSE) and (**b**) EMSE mechanism of the PET/CF composite boards.

3.4. The LOI of the PET/CF Composite Boards

For the PET/CF composite boards, the LOI decreases as a result of the addition of the CF woven fabrics. FR matrices are flame-retardant as their LOI is 30. However, the PET/CF composite boards have a LOI of 26. During the test, the composite boards can be set alight, but do not exhibit shrinkage or deformation, and the fire does not last once the samples are no longer in contact with flames. Theoretically, CF woven fabrics that are composed of carbon filaments cannot catch fire. However, the filaments can cause abrasion to the machine and thus are coated with an oiling agent before being fabricated into woven fabrics in order to decrease the friction force between carbon fiber and the machine. During the combustion process, the outer layers of the FR matrices are the first point that the flame contacts, and they are melted into liquid that covers the contact surface between them and the flame, as indicated in Figure 4a. The melt of the FR matrices then puts out the fire and stops the combustion. However, when the flame is continuously present and the flame temperature increases, the residual oil of the CF woven fabric is a flammable substance, and FR matrices thus cannot completely extinguish the combustion and form a carbonized layer over the PET/CF composite boards. This carbonized layer raises the temperature of the second ignition point, thereby preventing the sample from burning again and preserving the morphology of the PET/CF composite boards.

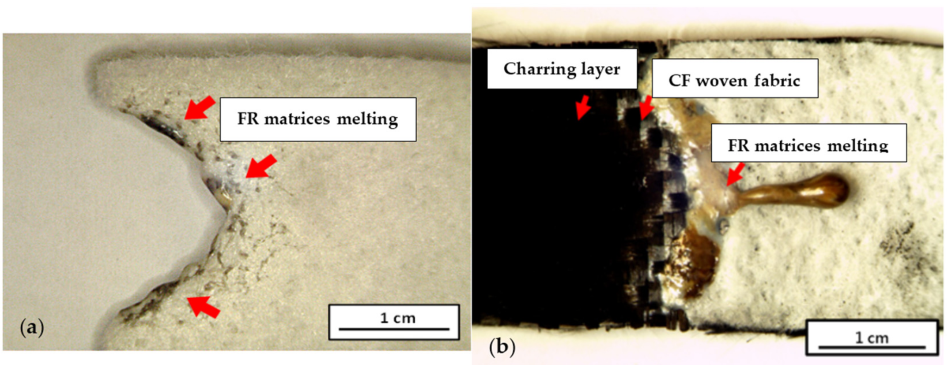

Figure 4. The combustion results of PET/CF composite board after the limiting oxygen index (LOI) measurement. (**a**) Pure flame-retardant (FR) matrices; (**b**) PET/CF composite board.

4. Conclusions

In this study, PET/CF composite boards that have good electromagnetic shielding effectiveness and thermal insulation were created. The test results indicate that PET/CF composite boards are significantly mechanically stronger than PET composite boards. Moreover, they have an EMSE of above 40 dB at a frequency of between 1.3 GHz and 3 GHz, namely a shielding rate of 99.99%. PET/CF composite boards are also highly thermally insulating and can maintain structural stability during the combustion process. PET/CF composite boards have thus proven to decrease the negative influence exerted by electromagnetic waves and provide thermal insulation and flame-retardant effects. Therefore, they are suitable for use in wall linings and coverings, interiors of transportation vehicles, and electronic products.

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Author Contributions: In this study, the concepts and designs for the experiment, all required materials, as well as processing and assessment instrument are provided by Jia-Horng Lin and Ching-Wen Lou. Data are analyzed, and experimental results are examined by Chen-Hung Huang, Chien-Lin Huang, and Yueh-Sheng Chen. The experiment is conducted and the text is composed by Ting-Ting Li and Yu-Chun Chuang.

Conflicts of Interest: The authors declare no conflict of interest.

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