

Process and Structure of Electromagnetic Shielding Plywood Composite Laminated with Carbon Fiber Paper

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Abstract: Carbon fiber paper (CFP), a type of flexible planer electromagnetic shielding material with thin thickness, low density, and good adhesion property and permeability, was laminated with wood veneer to produce a plywood composite with good shielding effectiveness (SE). It was found that a hot-press pressure of 1.2 MPa and a double-sized adhesive concentration of 380 g/m² were most appropriate for the production of CFP plywood composites. SE of plywood composite laminated with single layer CFP was better than that before hot pressed, which result from the formation of three-dimensional and smaller conductive carbon fiber circuitries. The space between two-layer CFPs and the thickness of the surface-layer veneer had significant influence on SE. The SE of the composites laminated with two-layer CFPs was significantly higher than those with one-layer CFPs. The SE in the frequency range of 30 MHz to 1 GHz reached above 30 dB depending on the space between two-layer CFPs and the thickness of the surface veneer, which was sufficient SE for commercialization and the use of plywood composites.

Keywords: Carbon fiber paper, electromagnetic shielding, hot-press process, laminate structure, plywood composite.

1. INTRODUCTION

Wood is one of the most abundant biological materials, and timber products have been widely used in both structural and nonstructural applications such as furniture and building construction. However, timber products remain low-value added materials, especially for the products of fast-growing plantation wood, and many physical technologies have been attempted for the production of higher-value added products for the industry. One of the methods is to modify wood products in terms of their electromagnetic shielding functionality, and thus replace expensive and heavy metal shielding materials. This wooden functional material could also be used as shielding material to reduce harmful electromagnetic interference in the fields of military, precision instruments, and hospital equipment.

Electromagnetic shielding wooden composites have been studied for about 30 years, with concentration mainly on combining the conductive shielding with wooden elements and/or by high-temperature carbonization of wood constituents. Wood particles were coated with a layer of nickel by electroless plating technology [1-3], and the coated particles were then used for the production of particleboards, the SE of which could reach 40 dB in the frequency range of 10 MHz to 1 GHz [4]. Veneer has also been electroless-plated with nickel on its surface, and can reach an SE of 55-60 dB in the frequency range of 9 kHz to 1.5 GHz [5, 6]. The plywood made with the modified veneers by the

γ -aminopropyltri-hydroxysilane (APTHS) before being plated with nickel could achieve an SE of higher than 60 dB in the frequency range of 10 MHz to 1.5 GHz [7].

Metal nets [8], metal fiber [9-11], and conductive powder [12] have also been mixed with wooden materials to prepare shielding composites. Among them, the fiberboard versions with two layers of 60 mesh copper wire nets placed on the top and bottom surfaces, respectively, have achieved the highest SE of 60 dB in the frequency range of 9 kHz to 1.5 GHz. It was also reported that the SE was higher when the metal nets were laminated on the surface layer than when they were laminated on the interlayer [8]. Conducting polymers, such as polyaniline and polypyrrole, were also applied in the wooden shielding material by in situ polymerization, and had an SE level above 10 dB in the frequency range of 100 MHz to 3 GHz [13]. Power coal carbon material was used to modify wood wool-cement boards. When the concentration of carbon material was 5wt% and 25wt%, the total insertion loss of electromagnetic wave in the frequency range of 2.5 GHz to 6 GHz could reach 20 dB to 40 dB [14]. Carbonized wooden material, such as solid wood panel [15] and fiberboard [16] could also improve SE, which could be further improved with structural designing. It was reported that the fiberboard composite designed with the metal net and conductive coating as reflective material on the two surface layers and barite powder and magnetite powder as an absorbing material in the core layer [17] could obtain an SE of more than 60 dB in the frequency range of 18.85 MHz to 1.46 GHz. The above studies on wooden shielding material could more or less enhance SE. However, further research is required to reduce costs and weight and improve processing efficiency.

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Because of its excellent electromagnetic property and mechanical performance, as well as its low density compared with metal, carbon fiber has recently been studied as a viable material in shielding fiberboard composites [18]. The carbon fiber was mixed with wood fiber (weight ratio 3:1) to make composites reaching 47.89 dB in the frequency of 1 GHz. One-layer nickel-plated carbon fiber (12 k) with grid arrangement was also laminated with medium density fiberboard substrate to make composites, and were reported to achieve a SE of 41.54 dB to 63.73 dB in the frequency range of 200 MHz to 1 GHz [19]. Carbon fiber paper (CFP), which has a lower percentage of carbon fiber than the pure carbon fiber, low density (about 60 g/m²), low thickness (about 0.12 mm), better flexibility, good conductivity, good SE, good compressibility, good adhesion property, good permeability, and moderate price, could be a potential material for the production of laminated wooden shielding composites. Therefore, the current study was proposed: the flexible CFP was laminated with wood veneer to produce a kind of electromagnetic shielding plywood composite.

2. TEST MATERIALS AND METHODS

2.1. Test Materials

Three types of veneers, *i.e.*, eucalyptus veneer with an average thickness of 2.4 mm, poplar veneer with an average thickness of 1.5 mm, and birch veneer with an average thickness of 0.4 mm and 0.8 mm. All veneers were dried to a moisture content of 7 to 9% by air drying, then cut into 250×250 mm sections.

CFP with a surface density of 60 g/m², carbon fiber concentration of about 35wt%(the rest is wood fiber), and a thickness of 0.12 mm was supplied by the Beijing Beyond Special Materials Co. Ltd. in Beijing, China.

Powdery modified urea-formaldehyde resin adhesive (UF) with a weight ratio of powder UF (C505) to modifier (M356) to curing agent (H271) to water of 100:15:15:60 was provided by Boshijiao Fendeli Adhesive Co. Ltd. of Shanghai in China.

A copper foil electrode was home-made with the following dimensions: 300 mm long, 10 mm wide, and 0.02 mm thick.

2.2. Test Methods

2.2.1. Electromagnetic Shielding Composites with Different Processing Parameters

Two groups of plywood composites were made: one for investigating the effect of pressing pressure and the other for exploring the effect of the adhesive concentration. Three-layer plywood composite was made with one-layer CFP inserted in one glue line between veneers, shown in Fig. (1). For the first group of plywood composites, the double-sided adhesive concentration was 280 g/m², the press time was 1.2 min/mm, platen temperature was 110±5 °C, and pressure was at 0.8, 1.0, 1.2, 1.6, 1.8, and 2.0 MPa, respectively. For the second group of plywood composites, double-sided adhesive concentration was 180, 230, 280, 330, 380 and 430 g/m², respectively, when the surface was bonded with the CFP, and 280 g/m² for those glue lines without CFP, press time was 1.2 min/mm, platen temperature was 110±5 °C, and pressure was at 1.2 MPa. The resistance of CFP before and

after hot pressed, SE of CFP before hot pressed, the SE and the bonding strength of plywood composites were measured.

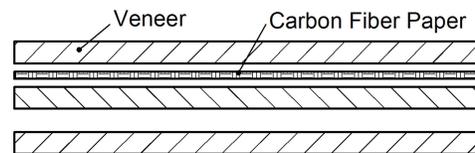


Fig. (1). Structure of three-layer plywood composite.

2.2.2. Plywood Composites with Different Structures

The first group of plywood composites was made as follows and the structure could be seen in Fig. (2).

Two layers of CFP were placed in different glue lines, and the double-sized spread adhesive concentration was 380 g/m² when the surface was bonded with the CFP and 280 g/m² in the glue line without CFP. The pressing time was 1.2 min/mm, platen temperature was 115±5 °C, and the pressure was 1.2 MPa. The number of veneers between two CFP layers was one (Fig. 2a), three (Fig. 2b), and five-layer veneers (Fig. 2c), respectively. SE was measured.

The second group of plywood composites was laminated with three and four layers of CFPs (Fig. 3). The other conditions were the same as in the previous group of plywood composites. SE was measured.

The third group of plywood composites was laminated with two-layer CFPs as in Fig. (2b) and Fig. (2c), but with surface-layer veneers of different thicknesses: 0.4 mm (birch veneer), 0.8 mm (birch veneer), 1.5 mm (polar veneer), and 2.4 mm (eucalyptus veneer). The other conditions were the same as in the previous group of plywood composites. SE was measured.

2.2.3. Drop Rate of Resistance Tests

The resistance of CFP before and after hot pressed was tested using the low-resistance testing instrument (TH2512). The drop rate of resistance was calculated as the percentage of difference between the resistance before and after hot pressed from the resistance before hot pressed.

Testing the resistance before hot pressed was done by placing two copper foil electrodes on the two ends of the CFP, as seen from Fig. (4). The two electrodes were applied with a certain pressure to impinge on the paper using a home-made clamp. The low resistance tester was used to test the resistance by connecting with the electrodes. The resistance after hot pressed was measured after the CFP with two electrodes on both ends was laminated with veneer and hot pressed.

2.2.4. SE Performance Tests

According to the Chinese standard “SJ20524-1995 measurement of SE of materials,” the plywood composite was formed into a disc with a diameter of 115⁰._{0.5} mm. The SE of the plywood composite was tested using a DN15115 type of vertical flange coaxial test device [19]. The test frequency range was 30 MHz to 1 GHz. The average value of two specimens was taken as the value of SE.

2.2.5. Bonding Strength Tests

The bonding strength of the plywood composite was tested in accordance with the Chinese standard “GB/T 9846-

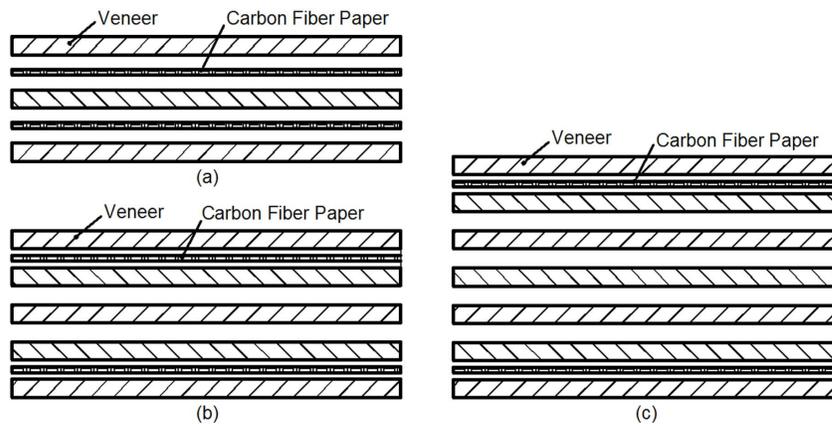


Fig. (2). Structure for plywood composites laminated with two-layer CFPs. (a) three-layer with two-layer CFPs; (b) five-layer with two-layer CFPs; (c) seven-layer with two-layer CFPs.

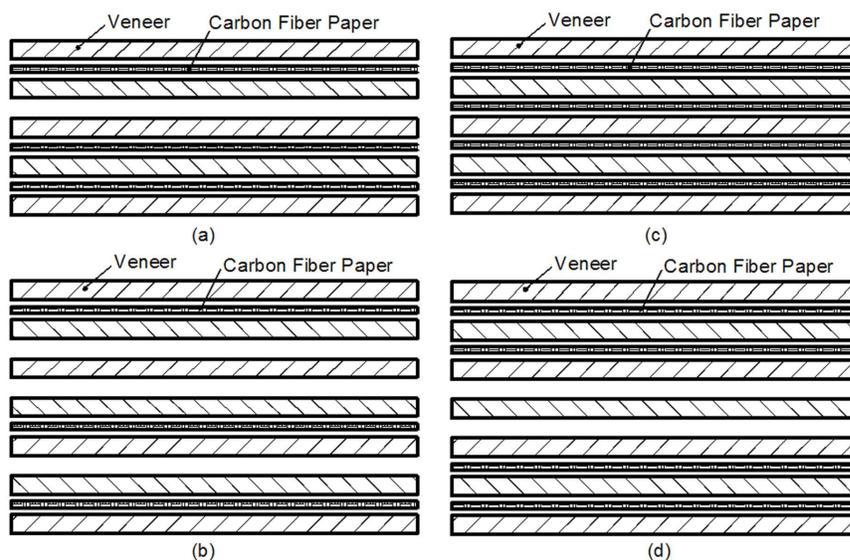


Fig. (3). Structure of plywood composites laminated with three and four-layer CFP. (a) five-layer with three-layer papers; (b) seven-layer with three-layer papers; (c) five-layer with four-layer papers; (d) seven-layer with four-layer papers.

2004 plywood” for the second type of plywood. First, the specimen was soaked in water at $(63\pm 3)^\circ\text{C}$ for three hours. Then the specimen was left to cool for ten minutes at room temperature. Finally, a universal mechanical testing machine was used to test the bonding strength of the specimen, and wood failure ratio was also recorded.

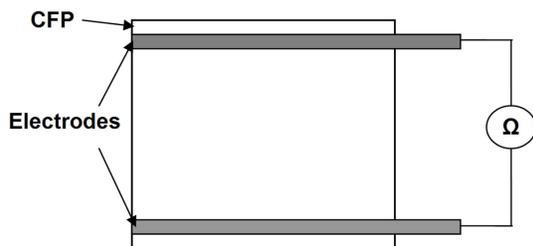


Fig. (4). Schematic diagram for testing resistance.

3. RESULTS AND ANALYSIS

3.1. Microstructure of CFP

A three-dimensional conductive net in the CFP can be clearly seen in Fig. (5), which showed that carbon fibers

were staggered. As the pressure increased, those fibers, which did not contact before press, may get touch, and those in partial contact (e.g., points A, B, C in Fig. 5) and the contacted carbon fibers (e.g., point D in Fig. 5), would have increased the contact surface, resulting in a reduction of resistance. Overall, the pressure range of 1.1 MPa to 2.1MPa is considered the most appropriate for the production of plywood composites, and using this parameter would give rise to a stable resistance.

3.2. Effect of Processing Parameters on Resistance, Bonding Performance and SE

3.2.1. Pressure

The reduction of resistance of CFP laminated with veneers after hot pressed is shown in Fig. (6). It can be seen that the drop rate of the resistance of the paper firstly increased, then decreased with the increase of hot press pressure as discussed in the previous section. The highest drop rate was 43.8% at a pressure of 1.8 MPa, and it was reduced to 39.8% at a pressure of 2.0 MPa. This may be because the fibers were dislocated from their original

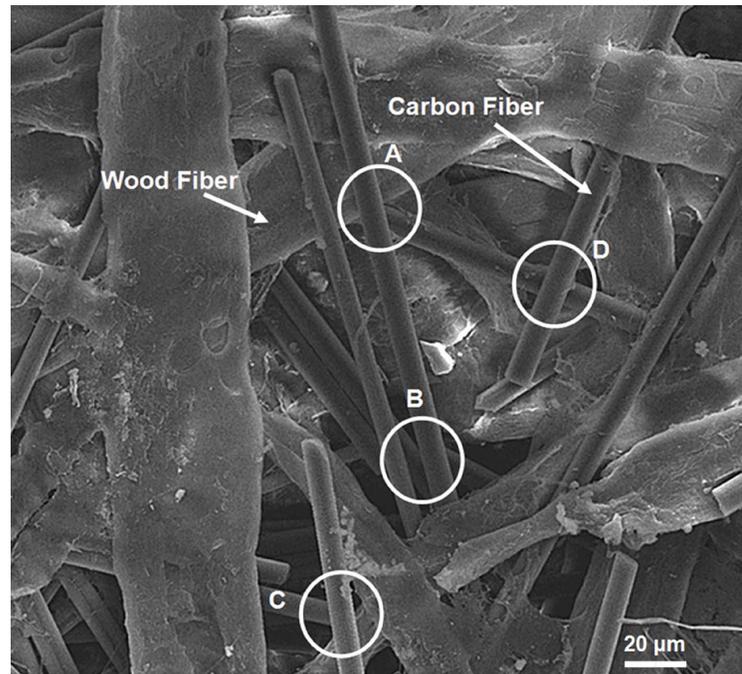


Fig. (5). SEM for CFP before hot pressed.

position to another position under sufficiently high pressure or fracture of the fibers shown as Fig. (7a), which could damage the conductive circuit composed of parts of fibers and cause the increase of resistance. However, the increased pressure may also result in closer contact among some parts of carbon fibers; therefore, the test results depend on the balance of the increase and decrease of the resistance. The above results indicate that the pressure from 1.2 MPa to 1.8 MPa could be more suitable for hot-pressing plywood composites.

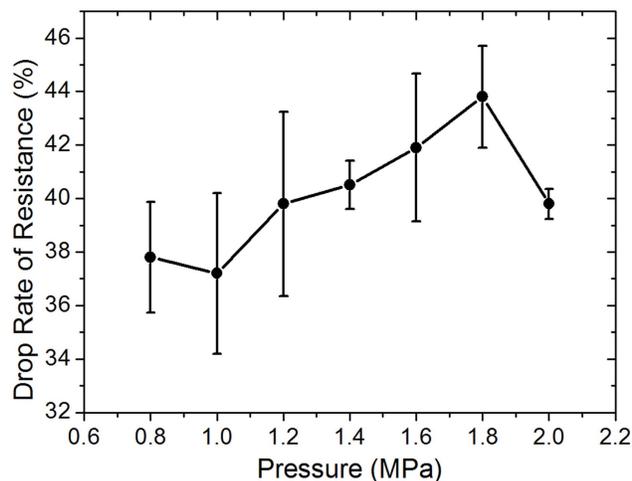


Fig. (6). Drop rate of resistance of CFP after hot pressed with different pressure.

As shown from Fig. (8), the SE of single layer CFP before hot pressed was lower than that of the plywood composite for all the frequency ranges tested in this study. More conductive micro circuitries should have been formed by carbon fiber contacted more closely after hot pressed. What is more, Fig. (7b) shows that the mesh of these circuitries become smaller and it is three-dimensional.

Generally, the mesh, contact resistance and electrical conductivity of the carbon fiber circuitries all have an impact on its electromagnetic shielding effectiveness [20]. When external electromagnetic wave are shot to the surface of three-dimensional conductive circuitries, it would inevitably cause magnetic flux change when passing through each micro circuitry, and then produce induced current and inductive magnetic field in circuits which could prevent the magnetic flux from changing in the circuit surface. According to Faraday's law of electromagnetic induction, the reversed magnetic field produced by the induced current in circuitry could offset external magnetic flux, and thereby reflect and shield external magnetic field [20]. On the other hand, the reflected wave is again reflected by other smaller circuitry in the three-dimensional conductive structure, which results in that magnetic field further weaken. Consequently, the SE after hot pressed was higher than that before hot pressed.

However, the influence of hot press pressure from 0.8 MPa to 2.0 MPa on the SE of plywood composites was insignificant, even though there was an obvious change of resistance under different pressures shown in Fig. (6), which was further confirmed by the calculated average value of SE (Table 1). It can be seen from Table 1 that the average bonding strength of plywood composites increased with the increase of pressure from 0.8 MPa to 2.0 MPa, more and more adhesive may penetrate into the paper and solidified by which bonding among carbon fibers can be strengthened, but stabilized afterward.

3.2.2. Adhesive Concentration

Fig. (9) shows that, the resistance of CFP compacted between two veneers by adhesion decreased with the increase of the adhesive concentration, with the drop rate changing from about 31.2% to 43.8% when the adhesive consumption changed from 180 g/m² to 330 g/m².

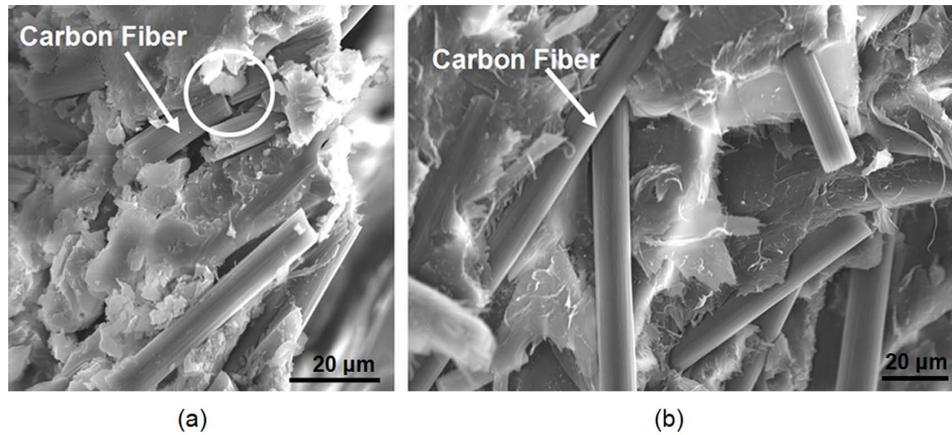


Fig. (7). Carbon fiber in the carbon fiber paper after hot pressed. (a) fracture of carbon fiber; (b) three-dimensional structure among carbon fibers in thickness.

During the hot press, the adhesive may have penetrated into the paper and solidified shown in Fig. (10b), which made the carbon fibers contact closer and not detach from each other for the compression stress after hot pressed. However, further increase of adhesive concentration resulted in a reduction of drop rate of resistance, and this may be because the excess adhesive could have penetrated into two contacted carbon fibers and resulted in the decrease of drop rate of resistance, which can be verified by the SEM in Fig. (10c) that the space among carbon fibers was apparently filled by adhesive.

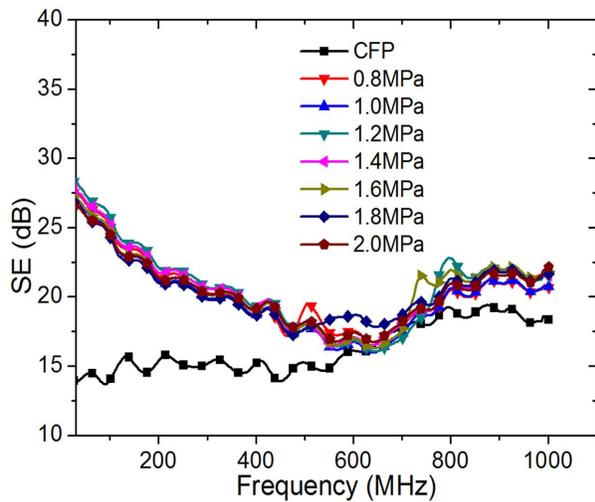


Fig. (8). SE of single layer CFP before hot pressed and plywood composite under pressure from 0.8 MPa to 2.0 MPa.

Fig. (11) shows the influence of adhesive concentration from 180 g/m² to 430 g/m² on SE was not significant. The average calculated SE also supported this finding (Table 2). As for the same mechanism above, it is also found that the SE of single layer CFP before hot pressed was lower than that of the plywood composite for all the frequency ranges tested.

However, the bonding strength increased from 0 MPa to 1.31 MPa when the adhesive concentration changed from 180 g/m² to 380 g/m², and after that the bonding strength

Table 1. Average SE and bonding strength of plywood composites.

Pressure (MPa)	Average SE from 30MHz to 1GHz (dB)	Bonding Strength (MPa)	Average Wood Failure Ratio (%)
0.8	19.6	0.87±0.42	44
1.0	19.9	0.84±0.32	13
1.2	20.3	1.07±0.25	46
1.4	20.3	1.11±0.30	61
1.6	20.5	1.34±0.24	64
1.8	20.5	1.01±0.23	72
2.0	20.3	1.29±0.06	30

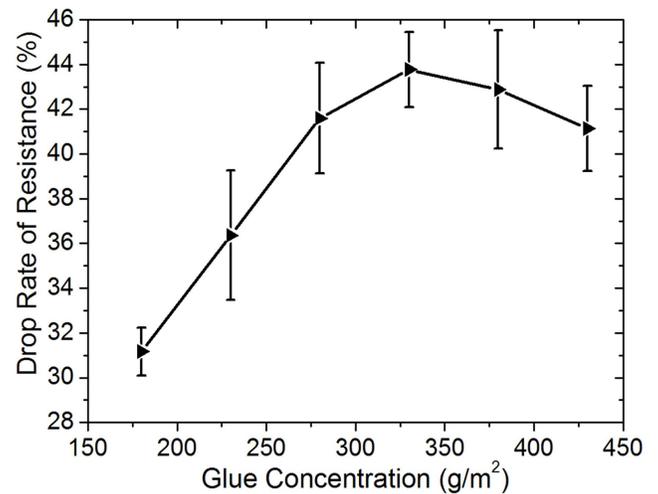


Fig. (9). Drop rate of resistance of CFP after hot pressed with different adhesive concentration.

started to decrease (Table 2). As in Fig. (10a), it is apparent that there was not enough adhesive to penetrate into the paper and the center layer of paper may not have been well-bonded by the glue when the adhesive concentration was 180 g/m². The bonding strength of the paper was very low

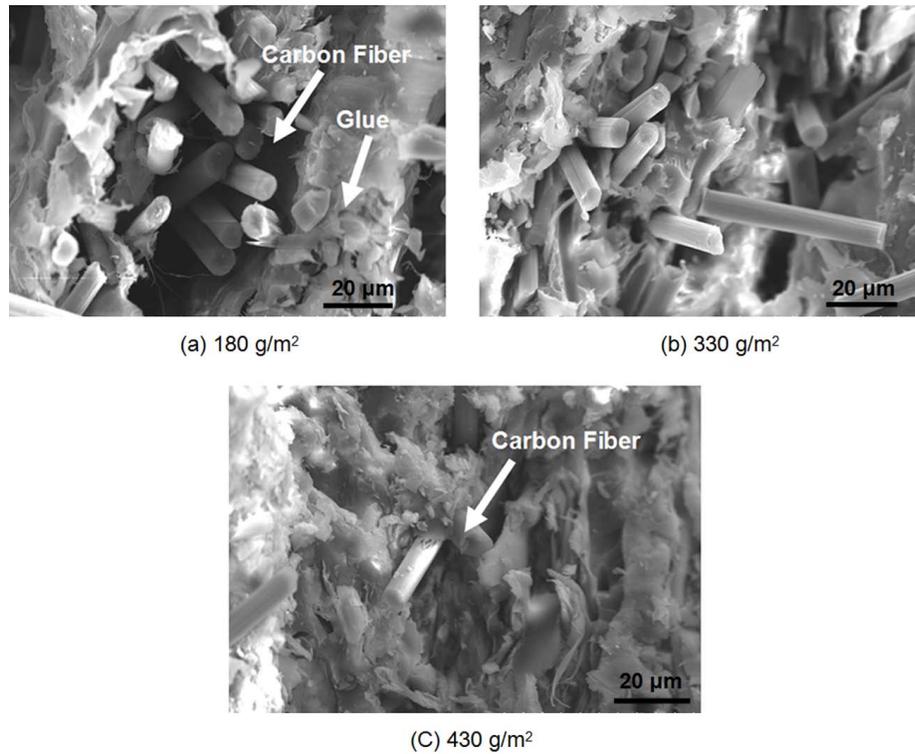


Fig. (10). SEM for cross section of the glued CFP with different adhesive concentration.

and hence, the specimen was easily delaminated when they were immersed in the hot water before being tested. When adhesive concentration was more than 330 g/m², adhesive fully permeated into the space among carbon fiber shown in Fig. (10b, c), consequently, the bonding strength was more credible.

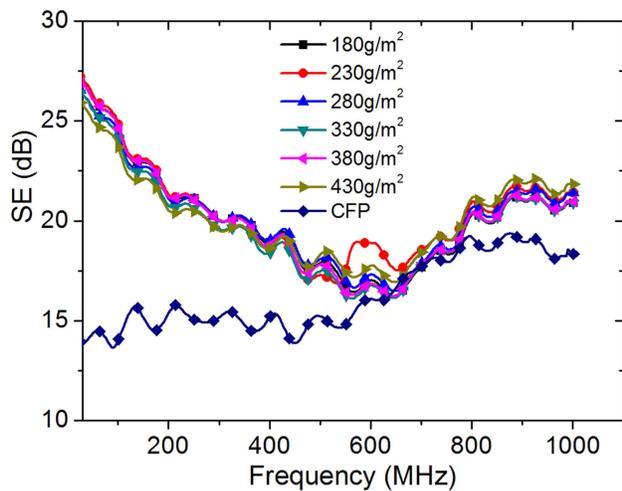


Fig. (11). SE of single layer CFP before hot pressed and plywood composite.

3.3. Effect of CFP and Veneer Combinations on SE

3.3.1. Plywood Composites Laminated with Veneer of Different Thickness Between Two-layer CFPs

Fig. (12) shows that, the number of veneer layers between two CFPs had a significant effect on SE. In the

Table 2. Average SE and bonding strength of plywood with different glue concentration.

Adhesive Concentration (g/m ²)	Average SE from 30MHz to 1GHz (dB)	Bonding Strength (MPa)	Average Wood Failure Ratio (%)
180	20.0	0	0
230	20.4	0.33±0.28	0
280	20.3	1.07±0.25	46
330	19.7	1.04±0.21	75
380	20.0	1.31±0.28	81
430	20.1	1.08±0.24	75

frequency range of 30 MHz to 1 GHz, the average SE of three kinds of plywood composite were 23 dB, 26 dB, and 28 dB, respectively.

Generally, reflection of electromagnetic wave occurs in interface between two kinds of shielding materials with different impedance [21]. So, the shielding change could be caused by the fact that the incident electromagnetic wave reflections were multiplied between the two-layer CFPs, which would further increase the loss of the reflected wave for certain dielectric properties of wood in the middle layer, which is shown as Fig. (13). The increase of thickness of the middle veneer would result in an increase in this loss. Similar phenomenon have also been found by Lee *et al.* [22], who concluded that the SE increased slowly with the increase of the thickness of L-layer (low conductive layer) in an H (high conductive layer)-L-H multilayer structure. The

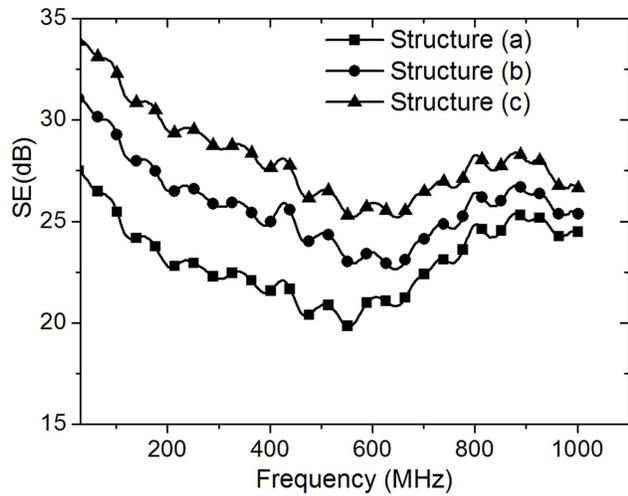


Fig. (12). SE of three different structures of plywood composite with two-layer CFPs. (a) three-layer with two-layer CFPs; (b) five-layer with two-layer CFPs; (c) seven-layer with two-layer CFPs.

results found by Ramadin *et al.* [23] showed that the SE of the spaced materials with 30 mm between two epoxy-carbon fiber fabrics was greater than those with 0 mm, 10 mm, and 20 mm spacing.

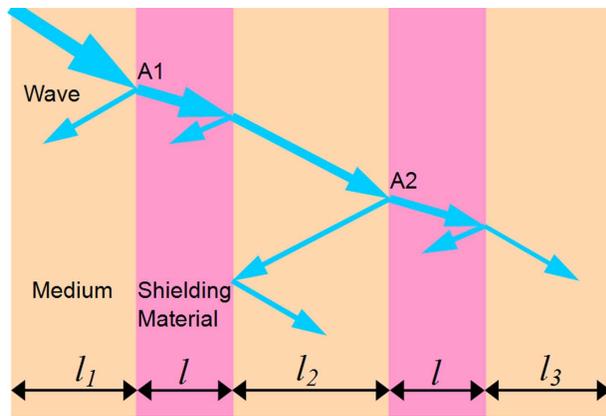


Fig. (13). Schematic diagram for double shielding (medium consists of 1, 2, 3-layer).

The shielding effect of the double-layers of composite can be further illustrated in Fig. (13), in which the double-layers were metal shielding materials and the interlayer medium (l_1 , l_2 , and l_3) is air. When shielding layers have the same thickness, the related calculation equation of total shielding effectiveness can be expressed as follows [24]:

$$SE = A + R + B_2 \tag{1}$$

A is the absorption loss, R is the reflection loss, and B_2 is the multiple reflection loss.

$$A = 2 \times 8.686l \sqrt{f \mu_r \sigma_r} \tag{2}$$

$$R = 2 \times \left[201g \frac{\left| 1 + \frac{\eta}{Z_w} \right|^2}{4 \left| \frac{\eta}{Z_w} \right|} \right] \tag{3}$$

$$B_2 = 201g \left| 1 - q_1 e^{-2\gamma l} \right| + 201g \left| 1 - q_2 e^{-j2\beta_0 l_2} \right| + 201g \left| 1 - q_3 e^{-2\gamma l} \right| \tag{4}$$

f is the frequency, μ_r is the electrical constants of initial magnetic permeability, σ_r is the electrical conductivity, η is the intrinsic impedance of sheet material, Z_w is the impedance of the incident wave, q_2 is the reflection coefficients of the shielding layer, l is the thickness of the shielding layer or interlayer, β_0 is the phase constant of the medium, and γ is the propagation constant of the medium.

It can be seen from Eq. (4) that B_2 is determined by the thickness (l) of the interlayer. The absolute value of the middle term in Eq. (4) increases with the increase of l_2 , which results in the increase of B_2 because of the increase of the distance of multiple reflections. Similarly, the increase in the SE of the plywood with the increase of thickness of interlayer between two CFPs could be ascribed to this mechanism.

The results of plywood composites laminated with three-layer CFPs, shown from Fig. (14), have further proved the influence of the thickness of space between two-layer papers on the SE, of which the SE of the (b) structure (Fig. 3) was greater than that of the (a) structure (Fig. 3) in full frequency range. The same result could also be observed with four-layer CFPs, shown from Fig. (15).

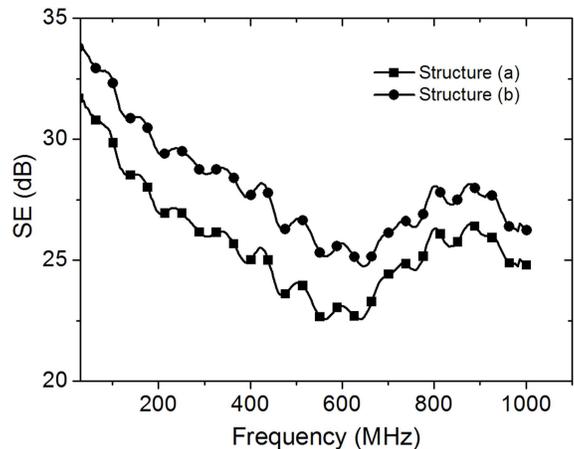


Fig. (14). SE of two different structure of plywood composites with three-layer CFPs.

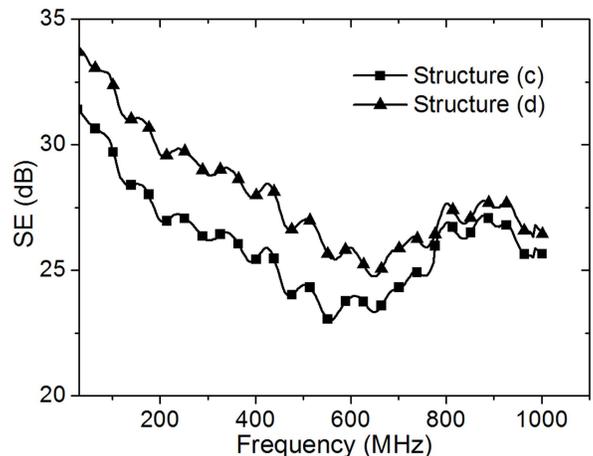


Fig. (15). SE of two different structure of plywood composites with four-layer CFPs.

3.3.2. Two-layer CFPs Plywood Composites Laminated with Surface Veneers of Different Thickness

It can be seen from Figs. (16, 17) that the thickness of surface veneer had a remarkable influence on its SE. The SE of plywood composites in the frequency range of 30 MHz to 1 GHz increased as the thickness of surface veneer decreased from 2.4 mm to 0.4 mm, which could be seen in both the five-layer plywood composites and the seven-layer plywood composites. The maximum difference reached about 10 dB. Overall, all SE in the frequency range of 30 MHz to 1 GHz reached above 30 dB when the thickness of surface veneer of five-layer plywood composites was 0.4 mm and that of seven-layer plywood composites was 0.4 mm and 0.8 mm, which met the requirement for commercial uses [25]. The SE in the seven-layer plywood composite with a surface veneer of 0.4 mm thickness had a maximum of 39 dB and a minimum of 34 dB in the frequency range. The dosage of carbon fiber was only 42 g/m², much lower than in previous studies, about 430 g/m² [19].

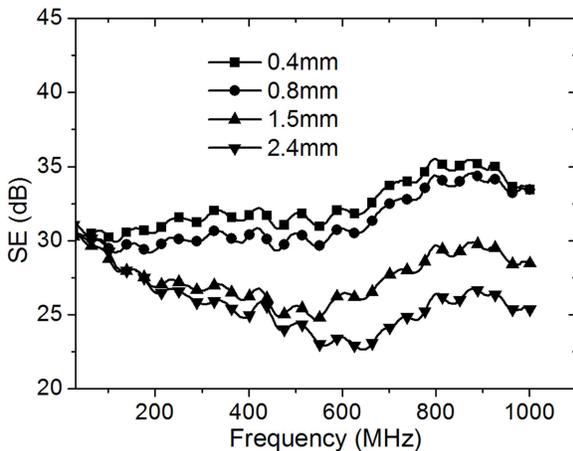


Fig. (16). SE of five-layer plywood composites laminated with surface veneer of different thickness.

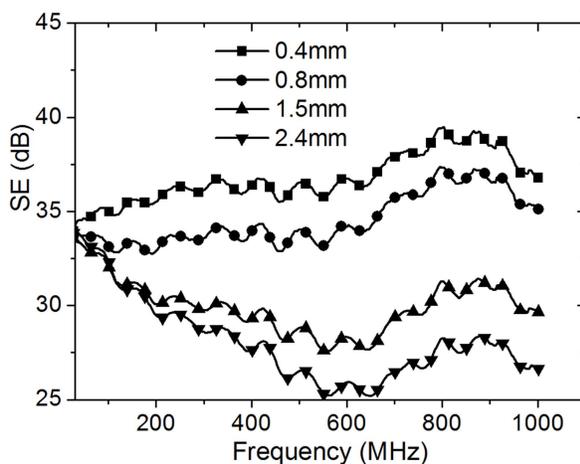


Fig. (17). SE of seven-layer plywood composites laminated with surface veneer of different thickness.

Wood material consists of polar materials, *i.e.*, moisture, cellulose, hemicellulose, lignin, and a small amount of mineral material, and has some dielectric property [26]. Its wave impedance is greater than that of air; when an electromagnetic wave passes from air into the surface veneer,

it gives rise to a refraction, the angle of which is less than that of incidence. As shown in Fig. (13), l_1 as surface veneer, also l_2 and l_3 as veneer, with the increase of the thickness of surface veneer the incident position (A_1) should move down and the incident position (A_2) also move down, so the distance of multiple reflection between two shielding material in finite width becomes shorter, which resulted in less SE.

CONCLUSION

- (1) Electromagnetic shielding plywood composites laminated with CFP were investigated, illustrating that CFP is a promising material for realizing an industrial production of wooden composites with sufficient SE.
- (2) It was demonstrated that CFP paper and wood veneer can appropriately laminate with a pressure of 1.2 MPa, a modified UF adhesive concentration of 380 g/m² (surface of veneer contacted with CFP), a press time of 1.2 min/mm, and a platen temperature of 110±5 °C.
- (3) Both the space between two-layer CFPs in plywood composite and thickness of surface veneer had a remarkable influence on its SE, with the SE increasing as space increased and thickness decreased.
- (4) The SE of the five-layer plywood composites laminated with two-layer CFPs (dosage of carbon fiber 42 g/m²) reached above 30 dB in the frequency range of 30 MHz to 1 GHz when the thickness of its surface veneer was 0.4 mm; and the SE of the seven-layer plywood composites reached above 30 dB in the frequency range of 30 MHz to 1 GHz when the thickness of surface veneer was 0.4 mm and 0.8 mm. Therefore, both could be applied in commercial uses.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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