Medium Density Fiberboard (MDF) with Efficient Electromagnetic Shielding: Preparation and Evaluation

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Carbon fiber (CF)-filled fiberboard specimens for electromagnetic (EM) shielding applications were produced in this study by mixing CF with wood fiber (WF). The aim of this work was to study the panel properties with different loadings (1%, 2%, 3%, 5%, and 10%) of CF. The mechanical, physical, and electromagnetic interference (EMI) shielding properties of the produced medium density fiberboard (MDF) were analyzed. The shielding effectiveness (SE) of the CF1 sample was 23.5 dB to 35.0 dB in the frequency range of 8.2 GHz to 12.4 GHz. The maximum SE of 64 GHz to 76 dB was obtained for the CF10 sample. The investigation of the mechanical properties of MDF panel indicated that the modulus of rupture (MOR), modulus of elasticity (MOE), and internal bonding (IB) of the composite panels were less than those of the control panel. The MOR, MOE, IB, thickness swelling (TS), and water absorption (WA) of the panel with 1% CF (CF1) were 24.7 MPa, 2,510 MPa, 0.69 MPa, 14.5%, and 52.3% respectively. Generally, the MDF panels with 1% CF exhibited a greater ability for EM shielding applications because of their acceptable properties according to the EN 622-5 (2019) standard and appropriate EM shielding of at least 20 dB.

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INTRODUCTION

Medium density fiberboard (MDF), an important wood-based composite, has a homogenous structure and surface with smooth and tight edges that can be easily machined. These advantages have attracted considerable attention and led to the growth of the MDF market. The global production of MDF has grown at a rapid rate in recent years, reaching approximately 100 million m^3 in 2019 (FAO 2019). As a sustainable and eco-friendly product, MDF can be produced by combining wooden and non-wooden lignocellulosic fibers with resin under hot pressing conditions; the resulting MDF is widely used in many applications such as the manufacturing of cabinets, furniture, shelves, door frames, and wall paneling (Irle and Barbu 2010; Mantanis *et al.* 2018). The continued production and usage of wood-based panels (WBPs) is highly dependent on the creation of value-added features in the board. One of the most widely used features to increase these products' added value is adding the capability for shielding of electromagnetic waves.

The rapid growth of technology and the development of electronic and communication equipment has led to an increase in electromagnetic pollution, especially for indoor applications (Xing *et al.* 2018). In recent years, it has been revealed that electromagnetic waves are the fourth most intense source of common pollution after water, sound, and air (Jiang and Guo 2011; Shi *et al.* 2015). The increased use of electronic devices (such as cell phones, laptops, tablets, *etc.*) and the spread of electromagnetic waves into the environment has increased electromagnetic interference and illnesses such as abortion, breast cancer, and leukemia (Al-Saleh *et al.* 2013; Thomassin *et al.* 2013; Lu *et al.* 2014; Shi *et al.* 2015; King *et al.* 2016; Karteri *et al.* 2017). In order to control this phenomena, electromagnetic shielding is required to block electromagnetic radiation (Bonaldi *et al.* 2014; Lu *et al.* 2014; Karteri *et al.* 2017)

Electromagnetic shields are found in the defense industry, the absorption of harmful mobile waves, research laboratories, and the medical field. Metals and metal composites are the most common materials for electromagnetic interference (EMI) shielding (Karteri *et al.* 2017). Metallic materials offer adequate shielding for lower frequencies. However, metals have some disadvantages, such as a noticeable lack of shielding in higher frequencies, a high density, stiffness, susceptibility to corrosion, resources scarcity, and high cost (Jalali *et al.* 2011; Gamage *et al.* 2017; Karteri *et al.* 2017; Xing *et al.* 2018). Metal composite materials are widely used to overcome the disadvantages of pure metallic electromagnetic shields, and plastic composites are a widely preferred electromagnetic shield material.

Increased human awareness and technological progress have created a need for more sustainable technologies and products. So, much research has been focused on the development of green and sustainable products that are comprised of natural fibers (Li *et al.* 2010; Lou *et al.* 2012). As such, the development of electromagnetic shielding materials from sustainable and environmentally friendly resources has become an important issue for researchers in composite industries. Among them, lignocellulosic fibers have garnered a lot of interest in composite manufacturing due to their availability, biodegradability, low cost, low density, low accumulation in the environment, and effective waste management performance (Xia *et al.* 2016).

One of the most widely used strategies for making electromagnetic wave shielding is the dispersion of various carbon allotropes (graphite, carbon fiber (CF), carbon block, *etc.*) within polymer composites. This can increase the electromagnetic protection efficiency due to the high conductivity of carbons allotropes (Thomassin *et al.* 2013). Some research has been done on this field. Sohi and co-workers (2011) prepared a carbon-based EMI shielding composite by adding different carbon fillers (carbon black, CF, and carbon nanotubes) to ethylene-vinyl acetate copolymer. The highest EMI shielding performance was 35 dB with 20% CF in the frequency range of 8 to 12 GHz (X band). Joshi *et al.* (2013) obtained better EMI shielding effectiveness (SE) of a polyvinyl alcohol-matrix composite by adding graphene nanoribbon that was obtained at 60 dB in the X band. King *et al.* (2016) studied the single and synergic effect of carbon fillers (carbon black, graphite, and carbon nanotubes) on the EMI shielding performance in polypropylene resin matrix. The largest EMI shielding was obtained when fillers were used simultaneously (60 dB). In another study, a carbon nanofiber reinforced polyether ketone composite was prepared which showed a 40 dB EMI SE with 14% carbon nanofiber (Chauhan *et al.* 2016). Soares *et al.* (2016) fabricated an EMI shielding polymer composite composed from polystyrene and ethylene vinyl acetate filled with carbon black. The highest SE for this composite was 22 dB with 15% carbon black. In another work, graphene nanoparticles were applied in polylactic acid (PLA) to obtain an EMI shielding nanocomposite; the highest SE reported was 10 dB with 10% graphene nano plates (Kashi *et al.* 2016). Jeddi and Katbab (2017) investigated the synergic effect of carbon nanotube and carbon block fillers on a foamed polyurethane/rubber silicon composite, where a maximum SE of approximately 28 dB was obtained. All studies have shown that composites that contain carbon fillers are considered to be one of the most important options in the field of electromagnetic shielding. It seems that wood-based panel composites can be considered as one of the options in this field due to the advantages of using natural lignocellulosic fibers.

Wood components such as fiber, particles, and flake can combined with conductive material to produce high value-added wood-based electromagnetic shielding composites (Yuan *et al.* 2013; Hou *et al.* 2015). Wood-based electromagnetic shielding composites with metallic and carbon fillers have shown excellent properties, but metallic fillers have some limitations due to their high density, brittleness, expensive processing, and susceptibility to oxidation (Zhao *et al.* 2016; Zhan *et al.* 2018). In contrast with typical metal-based EMI shielding materials, research has shown that conductive polymer composites can overcome the disadvantages of metal-based EMI shielding materials (Zhao *et al.* 2016).

Among various carbon-based fillers, CF has gained more acceptance as a filler to produce EMI shielding composites due to its high specific strength, low density, chemical resistance, high strength modulus, and electrical conductivity (Jagatheesan *et al.* 2015; Zhao *et al.* 2016; Dang *et al.* 2018; Zhan *et al.* 2018; Rezaei *et al*. 2020). In one study, a wood-based electromagnetic shielding composite was fabricated by adding a CF sheet between two layers, which created a SE greater than 30 dB in the frequency range of 30 MHz to 1 GHz (Yuan *et al.* 2013). In another study, electromagnetic wood plastic shielding was prepared using 15% conductive CF as filler to achieve a SE of 25 dB (Lin *et al.* 2015). Kwon *et al.* (2013) made carbonized the MDF specimens at 800 °C to achieve an average SE value of 43 dB in the 10 MHz to 1 GHz range. Hou *et al.* (2015) found that electromagnetic shielding fiberboard made by isocyanate adhesive and more than 10% CF could have a SE above 30 dB. The CFs in this work were soaked in alcohol for pretreatment. In another work, CFs were applied in polyacrylamide/wood fiber to obtain an EMI shielding composite where the highest SE reported was 41.03 dB with 7.5% carbon fiber. The surface of wood fiber was coated with amid polymer (Dang *et al.* 2018). During the recent years, studies have been reported on making and evaluation of the CF-filled fiberboard as an EMI shielding composite (Hou *et al.* 2015; Chen *et al.* 2016; Dang *et al.* 2018). Considering these results, EMI shielding properties were acquired by filling CF into the fiberboards.

To improve the bonding between wood fiber and CF, different treatments were done. Hou *et al.* (2015) soaked CFs in alcohol for 8 h, followed by drying the CFs and mixing them with wood fiber in a blender. Dang *et al.* (2018) coated surface of wood fiber with amid polymer, then CF was added, and finally the whole suspension was ground for 6 h using a colloid grinder at 2880 rpm. Yuan *et al.* (2013) impregnated CF in nitric acid solution for 30 min then soaked it in ethanol for 15 min. On the other hand, isocyanate adhesive has been mostly used to make fiberboard in CF-filled wood-based composites (Hou *et al.* 2015; Zhu and Sun 2015; Chen *et al.* 2016). Yuan *et al.* (2013) used polyvinyl acetate emulesion as an adhesive. Importantly, the quantities of isocyanate and even phenol formaldehyde (PF) used today in the MDF industries are negligible, whereas urea-formaldehyde (UF) is the predominant adhesive used for MDF production (Mantanis *et al.* 2018). Nevertheless, further studies are still needed for alternative methods to produce EM-wood composite without pretreatments and using a conventional industrial adhesive such as UF in the MDF industry. Hence, the current study aimed to address the aforementioned issues by developing electromagnetic shielding fiberboard without any pretreatments for both CF and wood fiber and using urea-formaldehyde as adhesive. The special focus was to achieve suitable shielding fiberboard with the lowest percentage of CF. For this purpose, the effect of CF content on the mechanical properties and the EMI SE of the CF-filled fiberboard samples were evaluated to analyze the applicability of these composites.

EXPERIMENTAL

Materials

Unresinated WFs, primarily from hardwood tree species mixture (poplar, willow, alder, and *Ulmus minor*) were obtained from Khazar Caspian Co. (Mazandaran, Iran). The WFs had a moisture content of 4.5% prior to being resinated.

The CF was purchased from Weida Composite Material Co. (Nanjing, China). The CFs had an average length, diameter, and density of 6 mm, 6 μm, and 1.76 g/cm^3, respectively. The tensile strength and modulus values of the CFs were 3.5 GPa and 230 GPa, respectively, according to the technical data sheet.

The UF liquid resin was obtained from Resin Sazan Co. (Mazandaran, Iran). The UF resin had a viscosity of 345 cps, a pH of 7, a density of 1.26 g/cm^3, and a solid content of 64%. A 2% addition of ammonium sulfate (Merck, Darmstadt, Germany) based on the resin solid content was used as a curing agent (hardener) before the adhesive was applied.

Polymeric diphenylmethane diisocyanate (PMDI) was provided by Wanhua Chemical Groups (Tian Shan, China). The density and viscosity of the PMDI at 25 °C were 1.25 g/cm^3 and 250 cps, respectively. The resin had a solid content of 100% and a dark brown color.

Mixing of the CF and the WF

The CF was mixed with the WF using a wet process. First, the required amount of CF was dispersed in water using a laboratory RW20 mixer (IKA, Staufen, Germany) at 2,000 rpm for 10 min. Then, the WF was gradually added into the paste and mixed for another 10 min. The fibers from the mixture were drained and dried in an oven at 103 °C to a moisture content of 4.5%. The pure WF was named CF0. The mass ratio of CF to WF was set at 1%, 2%, 3%, 5%, and 10% based on oven dry weight of the WF, and these samples were classified as CF1, CF2, CF3, CF5, and CF10, respectively (Fig.1).

Fiberboard Production

The UF and isocyanate adhesives were mixed prior to being applied at a level of 10% and 2%, respectively, based on oven-dry weight of the CF/WF. The adhesive mixture was sprayed onto the fibers using a pneumatic spray gun. After blending, the resinated fibers were formed by hand into a 300 mm × 350 mm forming box to form a mat. Afterwards, the whole mat was pre-pressed and put in the laboratory hot press (RANJBAR Press, Isfahan, Iran). The press temperature, time, and pressure were maintained for all the panels' production at 185 °C, 300 s, and a specific pressure of 4 MPa, respectively. The final panel thickness and density were also controlled at 10 mm and 750 kg/m^3, respectively. After hot-pressing, the MDF panels were held in a conditioned room (20 °C, 65% relative humidity) for two weeks prior to testing.

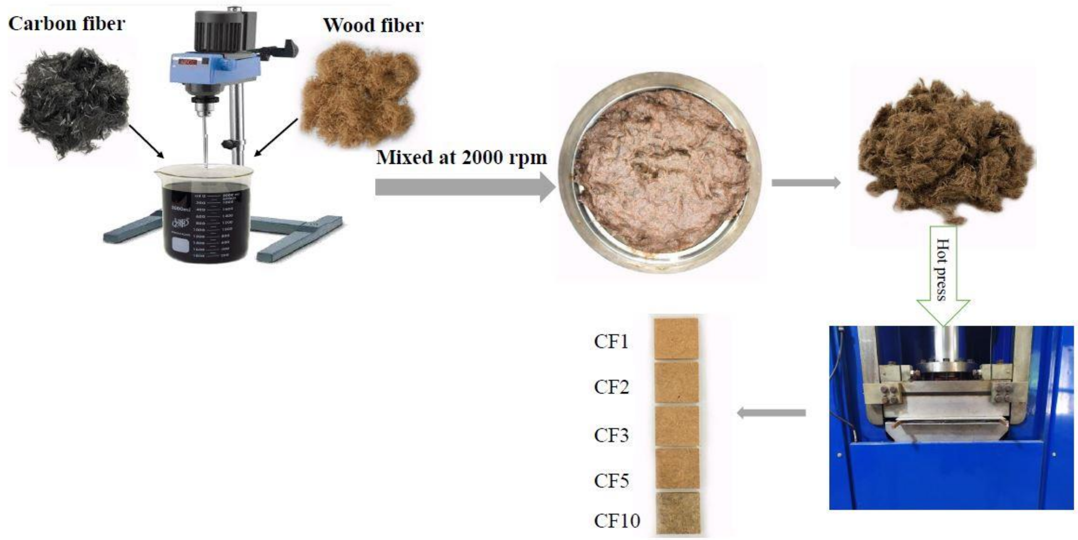


Fig. 1. Schematic for the production process CF-filled fiberboard

Microstructural Characterization

Morphological studies on the structure of MDF specimens were carried out using a Tescan MIRA3 XMU Field Emission Scanning Electron Microscope (FE-SEM) (Tescan, Brno, Czech Republic). For preparation, the samples were coated with gold layer prior to examination to avoid charging.

Panel Characterization

The panels were tested according to the international and European standards. The three-point bending test was carried out to determine the modulus of rupture (MOR) and modulus of elasticity (MOE). The panel samples were cut to dimensions of 250 mm^3 × 50 mm^3 × 10 mm^3 in accordance with EN 310 (1993). The internal bond (IB) strength was determined according to EN 319 (1993) on the 50 mm × 50 mm specimens. The thickness swelling was evaluated after 2, 24, and 48 h of water soaking according to EN 317 (1993) with the same dimensions that were used for the IB test. In the same test, the water absorption was also measured after 2, 24, and 48 h of water soaking, based on the initial mass of the samples.

The EM Shielding Characterization

The electromagnetic characterization of the panels were performed in the X band frequency (8.2 to 12.4 GHz) using a standard WR-90 waveguide setup and an Agilent E8364B 2-port vector network analyzer (Agilent Technologies, Santa Clara, CA, USA). The scattering parameters (S_{ii}) were measured. The power transmission and reflection coefficients can be written in terms of scattering parameters as,

$$T = |S_{12}|^2 = |S_{21}|^2 \quad (1)$$

$$R = |S_{11}|^2 = |S_{22}|^2 \quad (2)$$

The SE is defined as the ratio of the incident power to the shield to the transmitted power through the shield and can be represented as,

$$SE_T = 10\log_{10}(\frac{1}{T}) \quad (3)$$

$$SE_R = 10\log_{10}\left(\frac{1}{1-R}\right) \quad (4)$$

$$SE_A = 10\log_{10}\left(\frac{1-R}{T}\right) \quad (5)$$

where SE_T is the total shielding effectiveness, SE_R is the shielding effectiveness due to the reflection, and SE_A is the shielding effectiveness due to the absorption. From Eqs. 3 to 5 it is obvious that $SE_T = SE_R + SE_A$ (Mehranvari *et al*. 2017; Abolghasemi Mahani *et al.* 2018; Bizhani *et al*. 2018).

Statistical Analysis

A one-way analysis of variance (ANOVA) test was applied for the statistical analysis of the results through the SPSS software program version 26 (IBM, Armonk, NY, USA).

RESULTS AND DISCUSSION

Morphological Studies

Figure 2 presents the micromorphology of MDF without CF (CF0), with 1% CF (CF1), and with 10% (CF10). The FE-SEM images indicated that CFs were dispersed in the wood fiber matrix. As the CF increased from 1% to 10%, the CF became better visible in the wood fiber matrix.

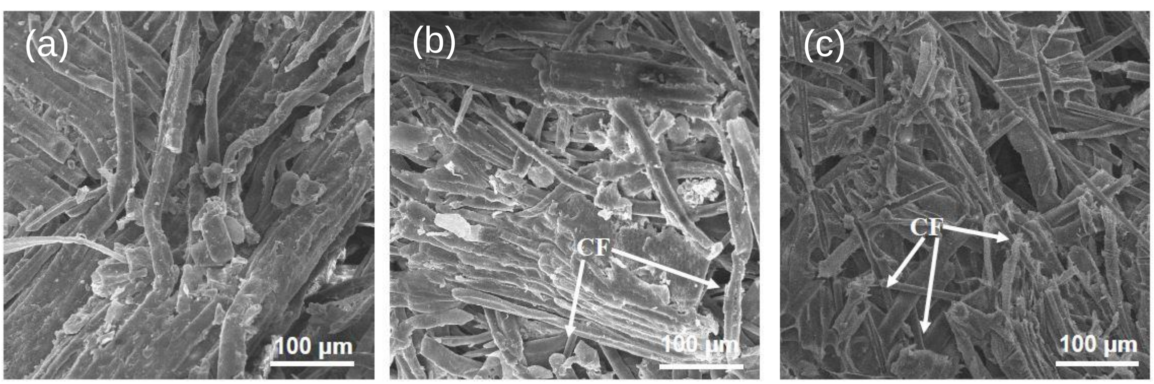


Fig. 2. The FE-SEM images (at 500X magnifications) from the surface of the MDF (a. CF0, b. CF10, and c. CF10)

The EM SE

An SE value of at least 20 dB corresponding to 99% blockage of incident EM waves is required for appropriate EMI applications (Mondal *et al.* 2016; Dang *et al.* 2018). The SE of the MDF panels with different percentage of CF are represented in Fig. 3. The control with no CF (CF0), had the lowest ability to shield EM radiation (2.3 dB at 8.2 GHz). When the CF was added to the MDF at 1% (CF1), the SE value increased to 23.47 dB at 8.2 GHz, and the maximum value was 34.95 dB at 12.4 GHz. By increasing the CF content in the MDF samples, the SE continuously increased to 64.28 dB at 8.2 GHz frequency with 10% CF loading. It appeared that the improving of SE could be related to the increased electrical conductivity of the samples. For the non-magnetic materials, electrical conductivity plays an important role in the EM SE (Dang *et al*. 2018).

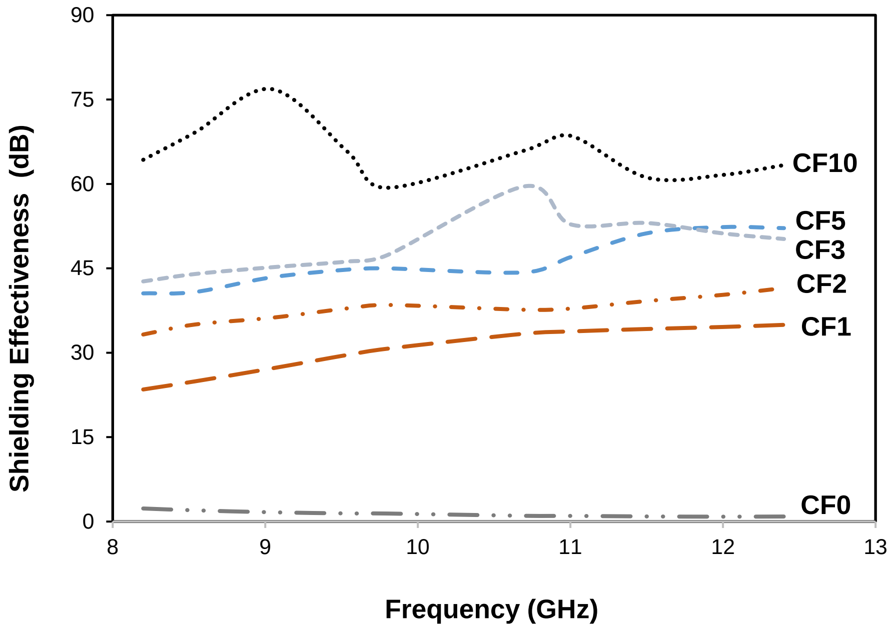
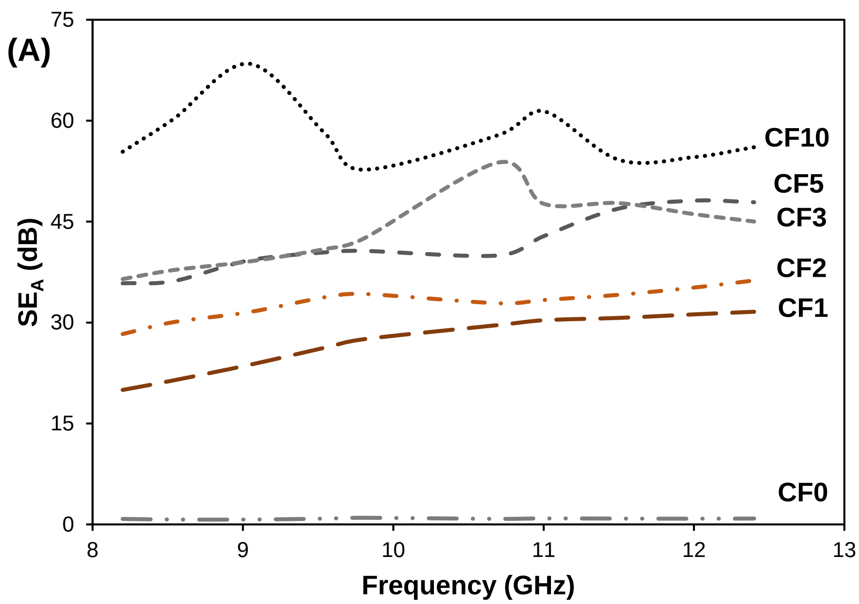


Fig. 3. SE_T of the MDF panels with different CF addition levels

The SE_A and SE_R calculated by the scattering parameters (S_{11} and S_{21}) are shown in Fig. 4. Both the SE_A and SE_R of the panels increased as the CF loading increased. The contribution of the SE_R was less than the SE_A for all the panels with different percentages of CF. The panel with 1% CF had SE_A and SE_R values of 19.98 dB and 3.48 dB, respectively. The SE_A values were 28.29 dB, 35.83 dB, 36.46 dB, and 55.38 dB and the SE_R values were 4.95 dB, 4.71 dB, 6.21 dB, and 8.89 dB for the panels with 2%, 3%, 5%, and 10% CF loading at the 8.2 GHz frequency, respectively. Therefore, the SE_A was the main contributor to the SE of the panels rather than the SE_R.



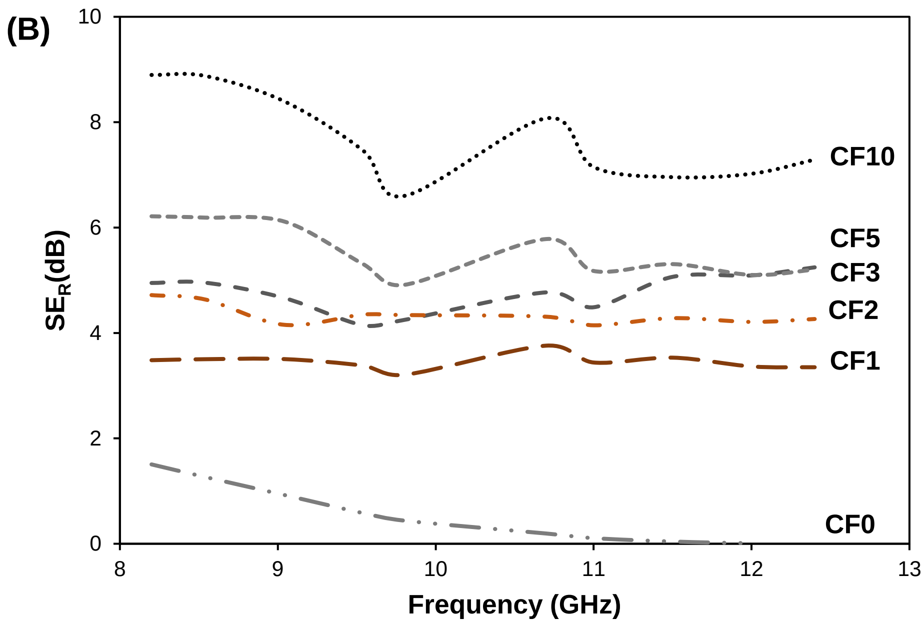


Fig. 4. The (A) SE_A and (B) SE_R values of the MDF panels with different CF addition levels.

Mechanical Properties

The IB strength

The IB strength tests revealed the strength quality of the resin bonding in the board's cross section after the hot-pressing process. The IB strength results for the MDF panels with different percentages of CF are shown in Fig. 5.

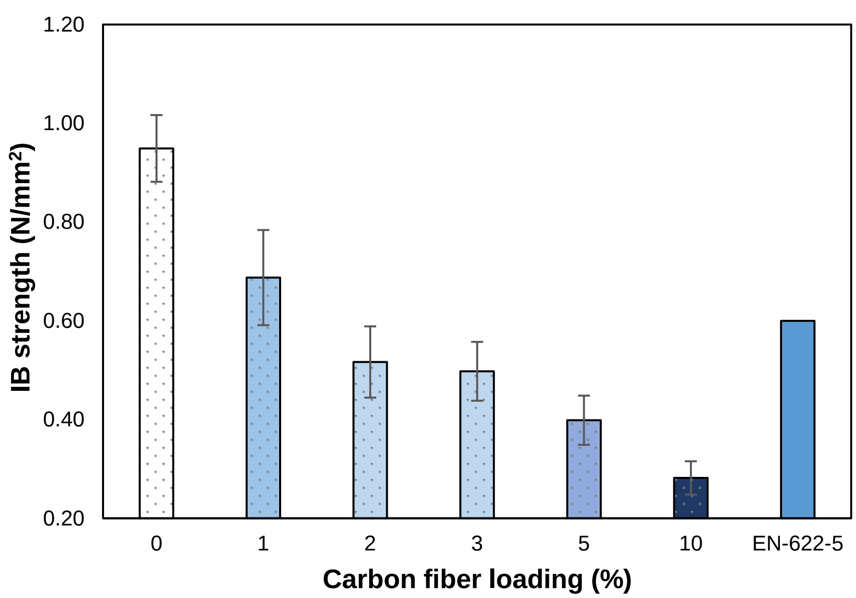


Fig. 5. The IB strength of the MDF panels with different CF loading rates

The CF10 MDF panel had the lowest IB (0.28 N/mm^2), while the CF0 MDF panel had the highest IB (0.94 N/mm^2). In other words, the IB strength decreased by approximately 70% as the CF loading increased from 0% to 10%. This may be attributed to the agglomeration of the CF/WF that creates regions for stress concentration as well as the poor interfacial adhesion between the CF and the WF. For a weaker the interfacial adhesion, less energy is needed to break the bonding connection (Khan *et al.* 2013; Hou *et al.* 2015; Kumar *et al.* 2017). The average IB value for the CF1 was 0.69 N/mm^2, which is higher than the required level according to the EN 622-5 standard (2009) (0.60 N/mm^2). Khan *et al.* (2013) also reported that the IB of panels with higher CF loading can easily fail due to the fiber agglomeration. This is consistent with the most reported results in this regard (Khan *et al.* 2013; Kumar *et al.* 2017).

The MOR and MOE

The effect of the CFs on the MOR and the MOE of the MDF panels is illustrated in Fig. 6. The MDF panel made with 10% CF (CF10) had the lowest MOR and MOE values of 18.4 MPa and 2,185 MPa, respectively. The MDF panels with no CF (CF0) had the highest MOR and MOE values of 27.8 MPa and 3,043 MPa, respectively. As the CF content increased from 0% to 10%, the MOE decreased from 3,043 MPa to 2,185 MPa. Moreover, by increasing the CF content up to 10%, the MOR decreased by approximately 35% in the CF10 panels. The reduction of the MOR and MOE values with the increased CF loading can be attributed to the weakened adhesion between the WF and the CF. The CF had nonpolar characteristics which cannot react with the UF adhesive. This can negatively influence the connection between the WFs and the CFs. In addition, the agglomeration of CFs and their uneven distribution between WFs can create local stress points (Khan *et al.* 2013; Kumar *et al.* 2017). The minimum required MOR and MOE values according to the EN 622-5 (2009) standard regarding conventional MDF panels for interior application are 22 MPa and 2,200 MPa, respectively. The CF1, CF2, and CF3 samples had higher MOR and MOE values compared to the EN 622-5 (2009) standard.

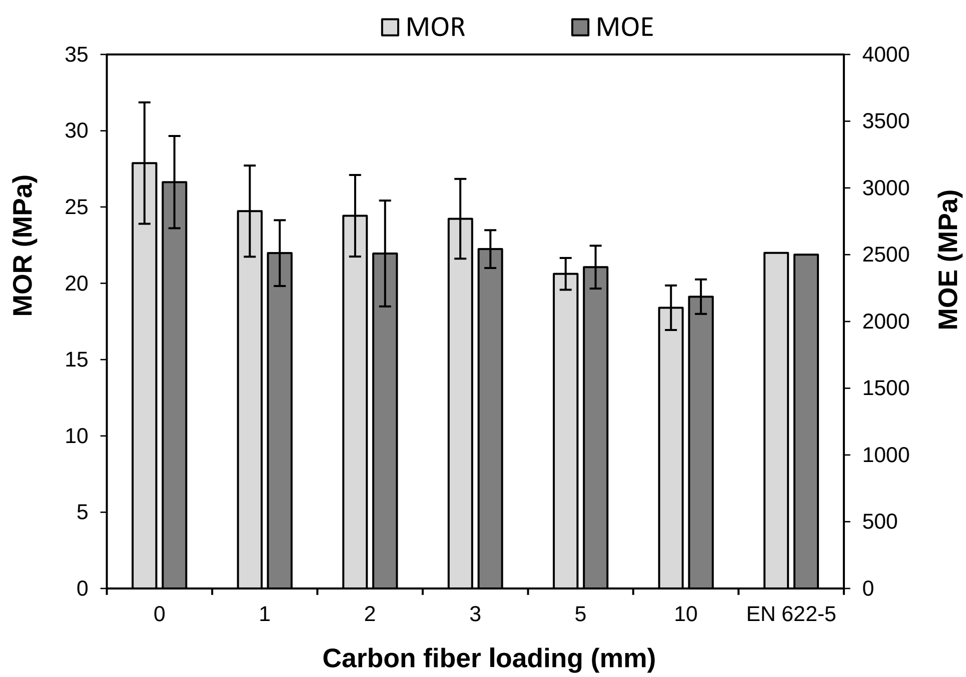


Fig. 6. MOR and MOE values for the MDF panels with different CF addition rates

Physical Properties

The thickness swelling (TS) and water absorption (WA) properties of the MDF panels after 2, 24, and 48 h of water soaking are shown in Fig. 7. The results showed that as the percentage of CF increased, the TS and WA properties of the MDF panels significantly increased. The TS after 2 h of water soaking ranged from 4% to 13.3% in the panels with 0% to 10% CF. The WA after 2 h of water soaking ranged from 51% to 71% in the panels with 0% to 10% CF. Increasing the immersion time to 24 and 48 h significantly increased the TS and WA properties in the MDF panels with different percentages of CF. The 24 h of water immersion resulted in a TS that ranged from 14.5% to 22.01%. Similar trends were also reported by Auriga *et al.* (2020) and Hou *et al.* (2015).

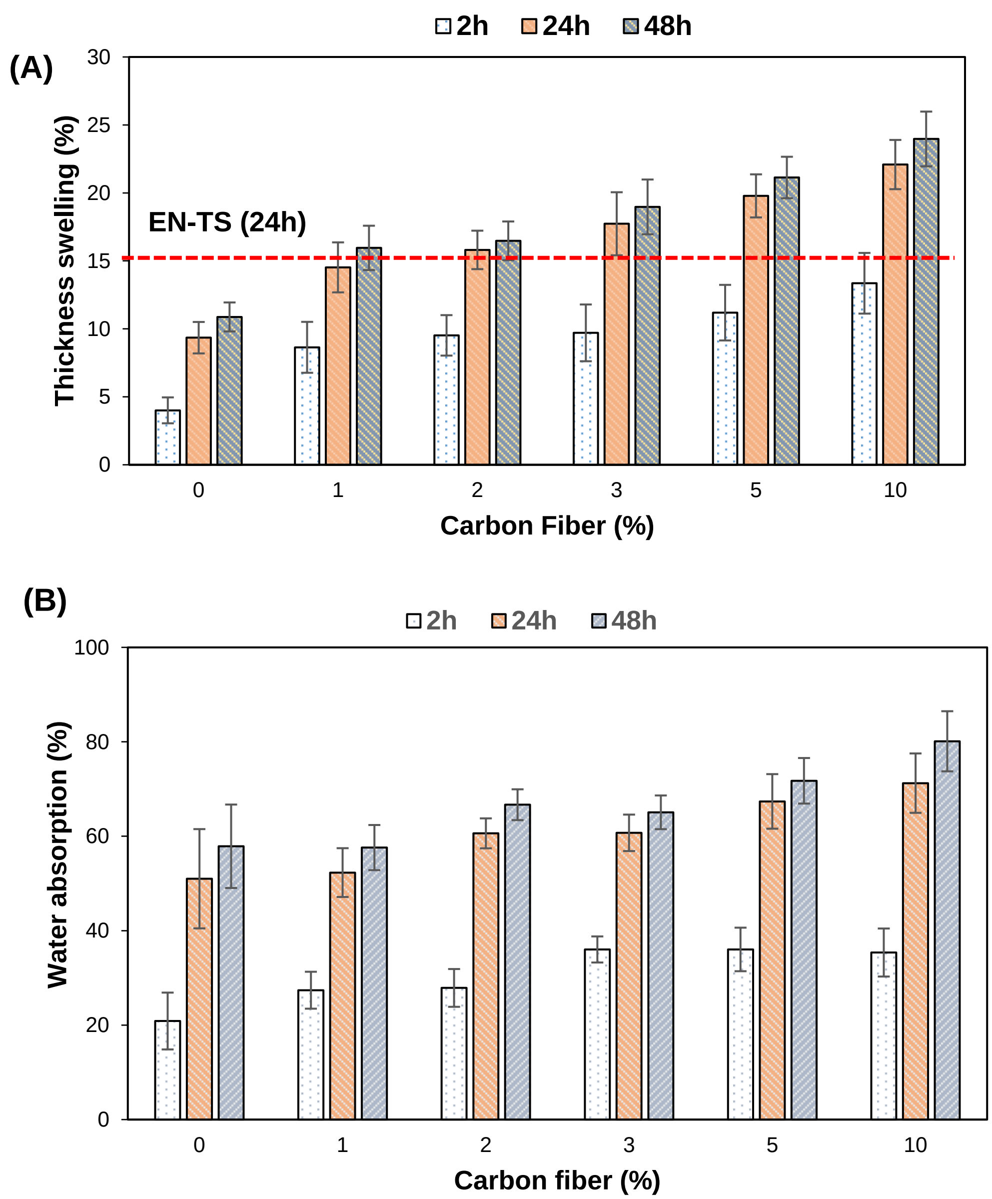


Fig. 7. The (A) TS and (B) WA properties for the MDF panels with different CF addition rates.

The increased TS and WA properties were attributable to the poor interfacial adhesion of the WFs and a weak connection between the WFs and the CFs. In addition, the agglomeration of CFs and the uneven distribution between the WFs prevented good adhesion at the interfacial zones. Furthermore, by increasing the immersion time in the water, it is difficult for CFs to maintain the adhesion form in the MDF, which increases the TS and WA properties (Khan *et al.* 2013; Hou *et al.* 2015).

The TS of the CF1 and CF2 samples met the minimum requirement for the TS (maximum of 15%) after 24 h of soaking for general-purpose MDF panels, based on the EN 622-5 (2019) standard for conventional MDF.

The properties of CF-fiberboard in this work is compared in Table 1 with those of panels having various content of CF with and without any pre-treatments. Although Dang *et al*. (2018) and Hou *et al*. (2015) reported favorable values of SET, MOR, and IB in their studies, but they used pretreatments (with alcohol and polyacrylamide), as well as isocyanate as adhesive and polyacrylamide for bonding between wood fiber and carbon fiber. It has to be mentioned that in the current study, the MOR and IB met the minimum requirement for properties according to EN 622-5 (2009) standard, while no pretreatment used and the conventional adhesive used for MDF production. On the other hand, the CF-filled composite in this work showed 35.0 dB EMI SE, which is more than their work. The amount of SE_R for carbon fiber (2.5% CF) reinforced polyacrylamide/wood fiber composite was high, which resulted in reflection of approximately 79% of the incident power from the shield. Therefore, 19.9% of incident power was absorbed. Nevertheless, the CF-filled fiberboard in the current work absorbed 46.3% of the incident power. This could be ascribed to the good dispersion of CF in wood fiber matrix using good blending with wood fiber in this work.

Table 1. Comparison between the Properties of CF-fiberboard

	Hou *et al.* (2015) with 1% CF	Dang *et al.* (2018) with 2.5% CF	Present study with 1% CF
Adhesive	10% pMDI*	Polyacrylamide	10% UF + 2% ISO
Pretreatment	With alcohol	Coated with Polyacrylamide	-
SE_T (dB)	25	25.27	34.97
SE_R (dB)	-	6.93	3.34
SE_A (dB)	-	18.21	31.6
IB	-	0.77	0.69
MOR	26	31	24.73

***** Polymeric methylene diphenyl diisocyanate

CONCLUSIONS

1. The electromagnetic interference (EMI) shielding medium density fiberboard (MDF) composites were fabricated using a carbon fiber/ wood fiber (CF/WF) mixture. The effect of different CF addition rates on the panel properties were examined. Within the frequency band from 8.2 GHz to 12.4 GHz, the shielding effectiveness (SE) of the CF1 panel was 23.5 dB to 34.9 dB. These values met the requirements for appropriate EMI applications (at least 20 dB). The SE of the panels increased as the CF loading content increased. A maximum SE of 64 dB to 76 dB was obtained for the CF10 panel. The

SE_A had a larger impact on the SE of the panels compared to the SE_R.

2. The internal bond (IB) strength of panels decreased significantly as the CF loading content increased. The average IB value for the CF1 panel was 0.69 N/mm^2, which was higher than the required level according to the EN 622-5 standard (2009) of 0.60 N/mm^2.
3. The modulus of rupture (MOR) and modulus of elasticity (MOE) bending properties of the MDF composite panels decreased as the CF content increased. In other words, the CF1, CF2, and CF3 samples had higher MOR and MOE values compared to the EN 622-5 standard (2009) for conventional MDF panels for interior applications.
4. The thickness swelling (TS) and water absorption (WA) physical properties increased as the CF content increased up to 10%. The 24 h of water immersion resulted in a TS that ranged from 14.5% to 22.1%.
5. The CF1 panel met the minimum requirements for appropriate EMI applications, and it passed the minimum requirement for properties according to the EN 622-5 (2009) standard which corresponds to conventional MDF for interior applications. This is a noteworthy achievement for wood-based EMI shielding composites.

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