Hybrid Effects of Carbon Fiber and Nanoclay as Fillers on the Performances of Recycled Wood-Plastic Composites

Young-Rok Seo,[a] Sang-U Bae,[a] Birm-June Kim,[a,]* Min Lee,[b] and Qinglin Wu [c]

Waste wood-plastic composite (WPC) was used in this work as a raw material to produce recycled WPCs reinforced with carbon fiber and nanoclay. To evaluate the synergistic effects of carbon fiber and nanoclay, various performances (*i.e*., microstrucural, mechanical, thermal, water absorption, and electrical properties) were investigated. Scanning electron micrographs and X-ray diffraction analysis of the fillers (carbon fiber and nanoclay) present in the recycled WPCs showed that the nanoclays were properly intercalated when filled with carbon fibers. According to mechanical property analysis, hybrid incorporation of carbon fibers and nanoclays improved impact strength, tensile strength, and flexural strength. However, further incorporation of nanoclays reduced the impact strength and did not improve the tensile modulus or the flexural modulus. The carbon fibers present in the recycled WPCs improved the electrical conductivity of the composites, despite the various fillers that interfered with their electrical conduction. In addition, carbon fibers and nanoclays were mixed into the recycled WPCs to improve the thermal stability of the composites. Finally, the presence of nanoclays in recycled WPCs led to increased water uptake of the composites.

Keywords: Wood-plastic composites; Waste resources; Recycled composites; Carbon fiber; Nanoclay

*Contact information: a: Department of Forest Products and Biotechnology, Kookmin University, Seoul 02707, South Korea; b: Timber Engineering Division, National Institute of Forest Science, Seoul 02455, South Korea; c: School of Renewable Natural Resources, Louisiana State University Ag Center, Baton Rouge, LA 70803, USA; *Corresponding author: bjkim3@kookmin.ac.kr*

INTRODUCTION

Since the late 1980s, researchers and industry have continued to enhance the properties of wood-plastic composites (WPCs) using coupling agents, sophisticated processing, and advanced formulations (Wolcott and Englund 1999). As a result, WPCs have attracted much attention due to their potential for outdoor applications, such as decking, fencing, railing, and industrial pallets. For the past several decades, the amount of waste WPCs has increased each year. Discarded WPCs are widely considered to be waste and should be recycled to reduce environmental impacts (Väisänen *et al.* 2016). As waste WPCs are recyclable resources, they must be recycled and used consistently. However, the performance of waste WPCs deteriorates when they have been exposed to outside conditions for an extended duration. Therefore, certain methods should be considered to address this problem.

Recently, several research approaches have been employed to investigate the use of reinforcing fillers to improve the performance of composite materials. Carbon fiber is the most utilized advanced reinforcing fiber material in polymer-matrix composites because of its good mechanical, thermal, and electrical properties (Van Hattum *et al.* 1999; Choi *et al.* 2000). Rezaei *et al.* (2007) used carbon fiber as a reinforcing filler for composites; they reported that the mechanical and thermal properties of polypropylene composites were improved by reinforcement with long carbon fibers. Further, Ameli *et al.* (2013) suggested that polypropylene (PP) composites reinforced with carbon fiber could be useful in fields where electrical conductivity is required.

Nanoclay consists of nano-sheets called layered silicates. It is used in various fields because it imparts composites with good mechanical properties, thermal stability, water and gas resistant properties, and flame retardancy, even if only a small amount is used for reinforcement (Ray and Okamoto 2003; Yasmin *et al.* 2006). This reinforcement strategy has also been applied in WPC manufacturing.

Zhou *et al.* (2014) showed that the mechanical and electrical properties of composites were improved when maleic-anhydride-grafted polyethylene was used to prepare WPCs filled with chopped carbon fibers. Hemmasi *et al.* (2010) reported that WPCs reinforced with nanoclay showed improved flexural moduli and tensile moduli. In addition, Gu *et al.* (2010) found that nanosized organo-clay present in WPCs slowed water penetration into the WPCs. Moreover, Khanjanzadeh *et al.* (2012) stated that, when nanoclay is used to reinforce polypropylene/wood flour composites, the presence of maleic anhydride-grafted polypropylene improves the compatibility of polypropylene, wood flour, and nanoclay.

More recently, Lee *et al.* (2017) reported that hybrid reinforcements consisting of two or more different types of fillers are more useful because they exhibit various properties not obtainable with a single reinforcement. As such, several previous studies show that composites reinforced with carbon fibers, nanoclays, or hybrid fillers exhibit improved performances.

Wood-plastic composites have been used in a variety of areas, which has increased the amount of waste WPCs. Therefore, studies should be conducted to reduce the environmental damage caused by waste WPCs, which represent a waste of resources. Numerous groups have attempted to manufacture WPCs by recycling waste wood and thermoplastic waste resources (Najafi *et al.* 2006; Adhikary *et al.* 2008; Chaharmahali *et al.* 2008).

However, relatively few experimental studies on the manufacture of recycled WPCs using waste WPCs have been reported. Thus, research on recycling waste WPCs should be conducted, and the demand for recycling is expected to increase gradually for the wide commercial application of WPCs as a sustainable resource. Hybrid reinforcement with fillers is a promising way to improve the performance of deteriorated waste WPCs (Seo *et al.* 2019). Previous studies have shown that reinforcement by carbon fiber and nanoclay in wood-free epoxy composites can have a synergistic effect (Iqbal *et al.* 2009; Khan *et al.* 2010).

Therefore, in this study, waste WPCs were recycled by hybrid reinforcement with carbon fiber and nanoclay. The aim of this study was to investigate the synergistic effects of carbon fiber and nanoclay on the microstructural, mechanical, thermal, water absorption, and electrical properties of recycled ternary hybrid composites (recycled WPCs) produced from waste WPCs.

EXPERIMENTAL

Materials

The waste WPC used in this study was obtained from KD Industries Co., Ltd., Hwaseong, South Korea; it consisted of wood flour, polypropylene, polyethylene, talc, and an ultraviolet (UV) stabilizer. It was dried at 60 °C for 4 day before compounding. Nanoclay was provided by Nanocor Co., Ltd. (Arlington Heights, IL, USA) as a master batch (nanoMax-PP) composed of 50 wt% of nanoclay, 25 wt% of polypropylene, and 25 wt% of maleic-anhydride-grafted polypropylene. Carbon fiber (T700S) was purchased from Toray Industries Co., Ltd. (Tokyo, Japan); the average fiber length was approximately 9 mm, and the fiber surface was polyester-sizing treated. Polypropylene (HJ700), which was added in the same amount as carbon fiber, was supplied by the Hanwha Total Co., Ltd. (Seosan, South Korea). It had a melting index of 22 g/10 min (230 °C/2.16 kg) and a density of 0.91 g/cm^3.

Methods

Manufacture of recycled WPCs

Waste WPCs, carbon fiber, and nanoclay were melt-compounded using a BA-19 co-rotating twin-screw extruder (Bautek Co., Ltd., Uijeongbu, South Korea) with a length-to-diameter (L/D) ratio of 40 and 8 temperature zones. The barrel temperature zones of the twin-screw extruder were 185 °C, 190 °C, 195 °C, 190 °C, 185 °C, 180 °C, 170 °C, and 120 °C, and the extruder rotation speed was 90 rpm. The extruded blends were pelletized using a BA-PLT pelletizer (Bautek Co., Ltd., Uijeongbu, South Korea).

Table 1. Formulation Ratios of Recycled WPCs Filled with Carbon Fiber and Nanoclay

Specimen	Composition Based on Weight (wt%)		
	Waste WPC	Nanoclay Composite	Carbon Fiber-PP Composite (CF / PP)
W-WPC	100	-	-
NC5	95	5	-
NC10	90	10	-
NC15	85	15	-
CFC20	80	-	20 (10/10)
NC5 CFC20	75	5	20 (10/10)
NC10 CFC20	70	10	20 (10/10)
NC15 CFC20	65	15	20 (10/10)
CFC40	60	-	40 (20/20)
NC5 CFC40	55	5	40 (20/20)
NC10 CFC40	50	10	40 (20/20)
NC15 CFC40	45	15	40 (20/20)
CFC60	40	-	60 (30/30)
NC5 CFC60	35	5	60 (30/30)
NC10 CFC60	30	10	60 (30/30)
NC15 CFC60	25	15	60 (30/30)
CFC100	-	-	100 (50/50)

The manufactured pellets were then fed into a BOY 12M injection molding machine (Dr. Boy GmbH & Co. KG, Neustadt, Germany) to produce standard test specimens of the recycled WPCs. The barrel temperature zones of the injection molding machine were 190 °C, 180 °C, 170 °C, and 120 °C. A total of 17 types of recycled WPC specimens were prepared with different formulation ratios of waste WPC, carbon fiber, nanoclay, and polypropylene. The formulation ratios for the recycled WPCs are shown in Table 1.

Microstructural characterization

The intercalation of the nanoclay in the composites was characterized by X-ray diffraction (XRD). For XRD analysis, an Ultima IV (Rigaku, Tokyo, Japan) equipped with a Cu Kα radiation source (λ = 0.154 nm, 40 kV, and 40 mA) was used, and samples were scanned at 3°/min at angles ranging from 3° to 15°. Based on Bragg's law (Eq. 1), the spacing of the layered clay platelets was determined from the 2θ position of the clay diffraction peak,

$$n\lambda = 2d\sin\theta \tag{1}$$

where n is an integer number of wavelength (n = 1), λ is the wavelength (nm) of the X-rays, d is the interlayer spacing of the clay in the composites, and θ is one-half of the angle of diffraction (°).

To more clearly observe the presence and surface morphology of the fillers present in the composites, after the Izod impact test, the fractured surfaces of the specimens were observed using a JSM-7401F (JEOL Ltd., Tokyo, Japan) field-emission scanning electron microscope. Specimens were platinum-coated (Sputter Coater 208HR; Cressington Scientific Instruments, Watford, England) and then analyzed at an acceleration voltage of 10 kV.

Mechanical properties

Izod impact strength tests were performed with a DTI-602B digital impact tester (Daekyung Technology, Incheon, South Korea) according to ASTM D256-10 (2010). Tensile and flexural strength tests were performed with a H50KS universal testing machine (Hounsfield, Surrey, England) according to ASTM D638-14 (2014) and ASTM D790-17 (2017), respectively. The test speed was set at 10 mm/min. At least five samples of each specimen were tested, and the average values were obtained.

Thermal properties

Thermogravimetric analysis (TGA) was carried out using a TGA/DSC 1 thermogravimetric analyzer (Mettler Toledo, Columbus, OH, USA) to investigate the thermal decomposition temperature of the recycled WPC specimens. The specimens were heated from 30 °C to 600 °C at a heating rate of 10 °C/min in a nitrogen (N_2) atmosphere.

Electrical properties

To evaluate the electrical conductivity of the specimens, their volume resistances were measured using a 4-point-probe Keithley 2401 electrometer (Keithley Instruments Ltd., Cleveland, OH, USA). Four samples of each group were measured, and their average values were calculated. The electrical conductivity σ was then calculated according to Eq. 2,

$$\text{Electrical Conductivity } (\sigma) = L / RA \tag{2}$$

where L is the distance (mm) between the electrodes, A is the cross-sectional area (mm), and R is the measured resistance (Ω).

Water absorption properties

Water absorption tests of the recycled WPC specimens were measured according to ASTM D570-98 (2018). For each formulation, specimens were immersed in distilled water at room temperature for 10 weeks. All values of the measurements were calculated as the mean of five specimens. After the measurements, the specimens were immersed again in distilled water prior to further measurements. The water absorption and thickness swelling were calculated using Eqs. 3 and 4,

$$\text{Water Absorption } (WA, \%) = (W_{\text{Wet}} - W_{\text{i}}) \times 100 \tag{3}$$

where W_{Wet} (g) is the weight of the specimen after immersion and W_{i} (g) is the weight of specimen before immersion,

$$\text{Thickness Swelling } (TS, \%) = (T_{\text{Wet}} - T_{\text{i}}) \times 100 \tag{4}$$

where T_{Wet} (mm) is the thickness of specimen after immersion and T_{i} (mm) is the thickness of specimen before immersion.

RESULTS AND DISCUSSION

Microstructural Characterization

X-ray diffraction was used to determine structural characteristics of the nanoclay used to fill in recycled WPCs (Kanny *et al.* 2008). The XRD patterns of various recycled WPCs are shown in Fig. 1, and the XRD analysis results are summarized in Table 2.

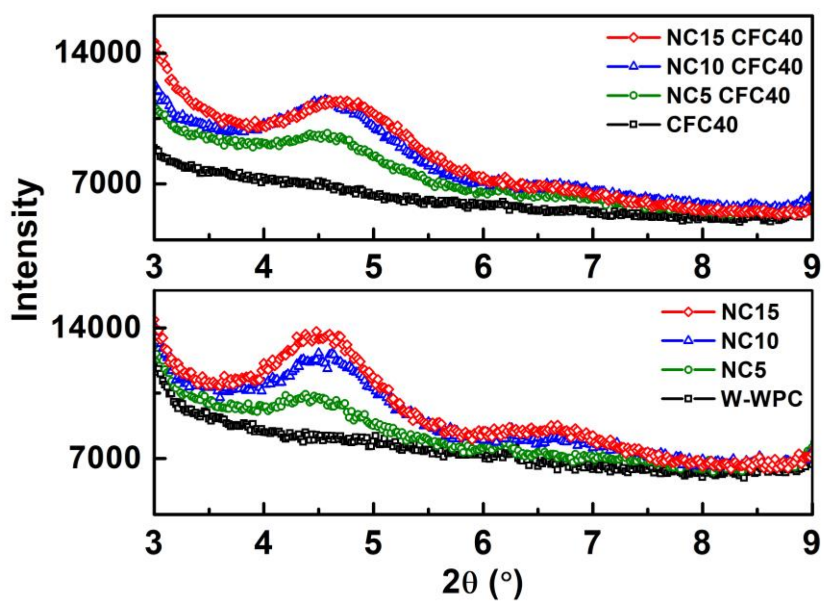

Fig. 1. The XRD patterns of recycled WPCs filled with carbon fiber and nanoclay

The nanoclay-filled composites were clearly identifiable from the XRD patterns, which indicated that the original crystal structure of the clay was partially retained (Dorigato *et al.* 2011). The XRD pattern of W-WPC showed no distinct peak, whereas that of the recycled WPCs filled with nanoclay without carbon fiber exhibited peaks. With increasing nanoclay content, the XRD patterns of the samples show peaks at similar 2θ values, and the width of the XRD peaks increased. These observations indicated that both the clay content of the original structure and the aggregation ratio of the clay increased (Rahman *et al.* 2012). The XRD peaks of the recycled WPCs filled with both carbon fiber and nanoclay showed similar 2θ values, and the width of the XRD peaks increased as the amount of nanoclay increased. This trend was similar to that of the composites without carbon fiber. However, the XRD peak positions shifted and the XRD peaks were narrower because, when carbon fiber and nanoclay are present together, a specific peak of the clay may not be detected due to the high fraction of carbon fiber (Bozkurt *et al.* 2007). Therefore, hybrid incorporation of carbon fiber and nanoclay may result in the disappearance or decrease in intensity of a specific XRD peak. Irrespective of the carbon fiber content, the *d*-spacing decreased as nanoclay content increased. This result suggests that, as the content of the nanoclay increases, aggregation may occur, and exfoliation may be limited.

Table 2. XRD Data for Recycled WPCs Filled with Carbon Fiber and Nanoclay

Specimen	2θ (°)	*d*-Spacing (nm)
W-WPC	-	-
NC5	4.38	2.01
NC10	4.50	1.96
NC15	4.60	1.92
CFC40	-	-
NC5 CFC40	4.42	1.99
NC10 CFC40	4.56	1.94
NC15 CFC40	4.60	1.92

Scanning electron microscopy (SEM) images of recycled WPCs are presented in Fig. 2. Figure 2(a) shows an image of the waste WPC only composite; the wood flour and other fillers that constituted the waste WPC showed good interfacial contact with the polymer matrix. Figure 2(b) shows an image of the composite with 15 wt% NC and 85 wt% W-WPC. Unlike Figures 2(a) and 2(b) that show fine nanoclay. Figures 2(c) and 2(d) show the differences in carbon fiber content. More carbon fibers were observed in the composite with 60 wt% CFC than in that with 20 wt% CFC. In addition, numerous voids were observed in the composite with 60 wt% CFC because of fiber pullouts. Figure 2(e) shows an SEM image of the composite with 60 wt% CFC and 40 wt% W-WPC, which exhibited good interfacial contact between the polymer matrix and the carbon fiber. Figure 2(f) shows an SEM image of the composite with 15 wt% NC, 60 wt% CFC, and 25 wt% W-WPC. In this image, the presence of nanoclay particles and interfacial contact between the carbon fiber and polymer matrix were observed throughout the fracture surface of the composite. These SEM images indicate that the proper incorporation of the fillers (carbon fiber and nanoclay) is important when manufacturing recycled WPCs based on waste WPC.

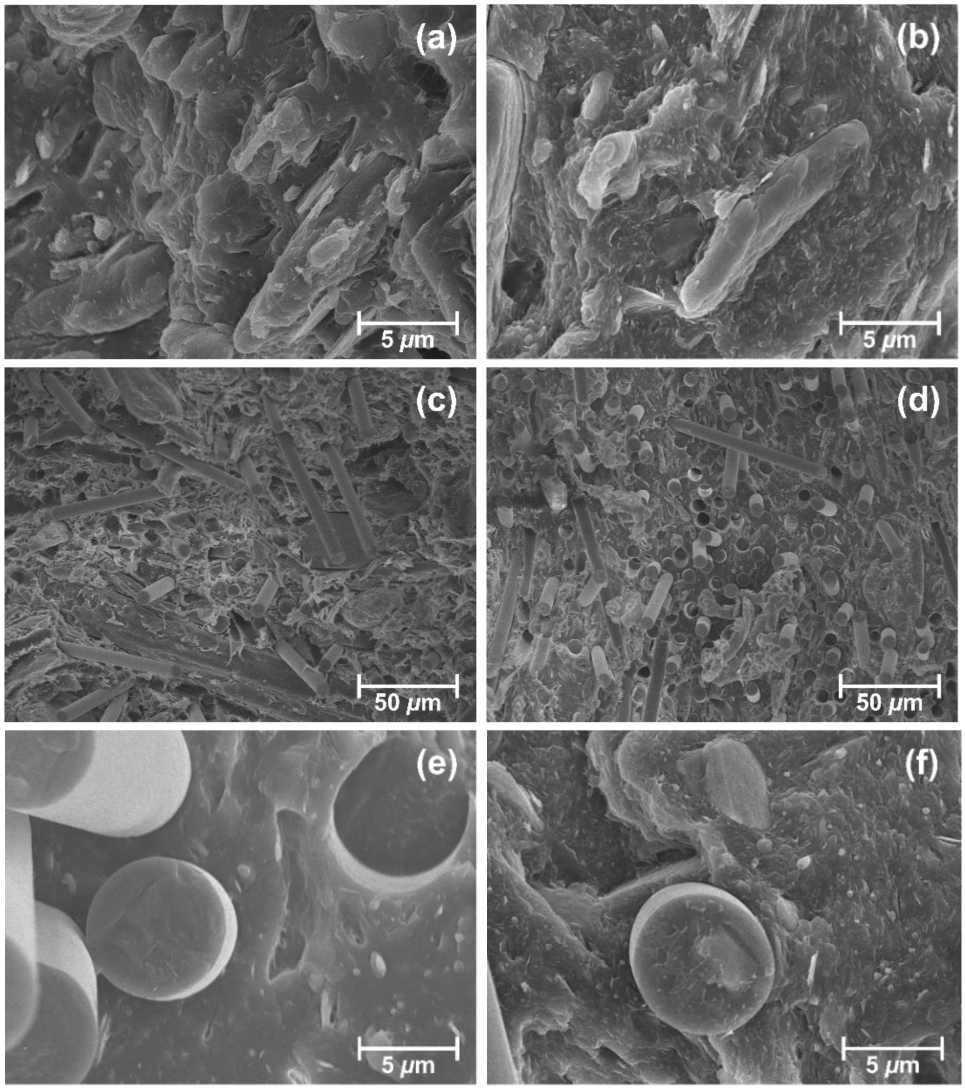

Fig. 2. The SEM images of the impact-fractured surfaces of recycled WPCs filled with carbon fiber and nanoclay: (a) W-WPC (5000×), (b) NC15 (5000×), (c) CFC20 (500×), (d) CFC60 (500×), (e) CFC60 (5000×), and (f) NC15 CFC60 (5000×)

Mechanical Properties

The impact strengths of the various recycled WPCs are shown in Fig. 3. The impact strength was increased with the incorporation of carbon fiber. The carbon fiber used in this study had a high aspect ratio and was a long fiber with a length of approximately 9 mm. Additionally, because the surface was a polyester-sizing-treated fiber, excellent interfacial bonding was achieved between the polymer matrix and the fiber. Therefore, the carbon fiber effectively absorbed the energy generated from the external impact and dispersed the stress (Unterweger *et al.* 2015). The impact strength increased with the incorporation of 5 wt% NC irrespective of the carbon fiber content but decreased with increasing nanoclay content. Nanoclay is a nano-sized filler with a platelet shape and high aspect ratio. When intercalation and exfoliation occur properly in the composite, it is well dispersed, and a subsequent toughening effect improves the impact strength (Ataeefard and Moraian 2011). Small amounts of nanoclays present in composites are appropriately dispersed between the carbon fibers and exhibit a synergistic effect, but when large amounts of nanoclays are present, nanosized fillers with large surface areas are agglomerated. Consequently, dispersing the impact is difficult and fracture failure occurs because of stress concentration (Chen *et al.* 2003). Thus, the impact strength was reduced.

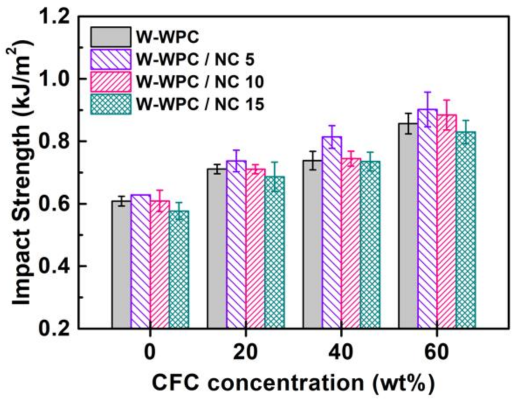

Fig. 3. Impact strength of recycled WPCs filled with carbon fiber and nanoclay

The tensile properties of the various recycled WPCs are shown in Fig. 4. The tensile strength improved with the incorporation of carbon fiber and nanoclay, which was likely due to the increased orientation of the carbon fiber in the longitudinal direction during the injection molding process. The polyester-sizing-treated carbon fiber and appropriately intercalated and exfoliated platelet-like nanoclay interfered with the debonding of the polymer matrix. Thus, the tensile strength improved overall. The tensile modulus of the composites increased with increasing incorporation of carbon fiber. Carbon fiber has greater stiffness than the other components of recycled WPC, which appeared to improve its tensile modulus (Turku and Kärki 2014). However, the incorporation of nanoclay did not strongly influence the tensile modulus because the carbon fibers, which were substantially larger than the particles of the nanosized clay, were already present in a high proportion; therefore, their contribution to the tensile modulus overshadowed that of the nanoclay.

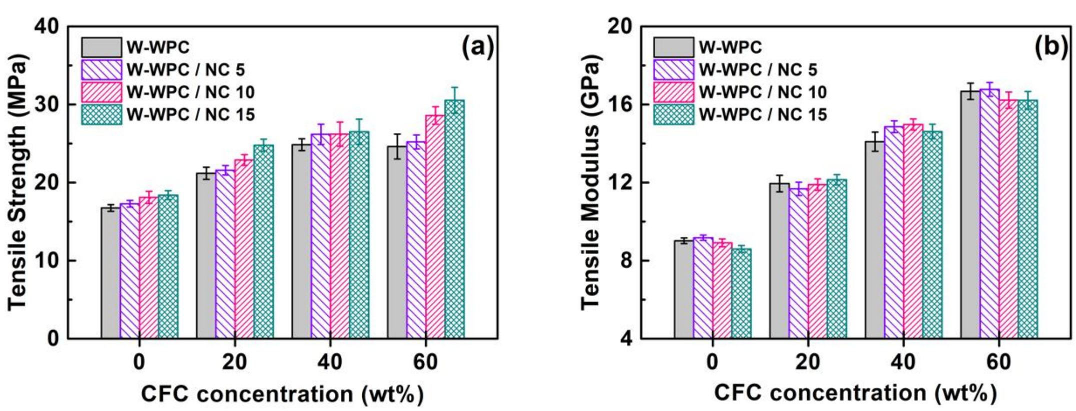

Fig. 4. Tensile properties of recycled WPCs filled with carbon fiber and nanoclay: (a) tensile strength and (b) tensile modulus

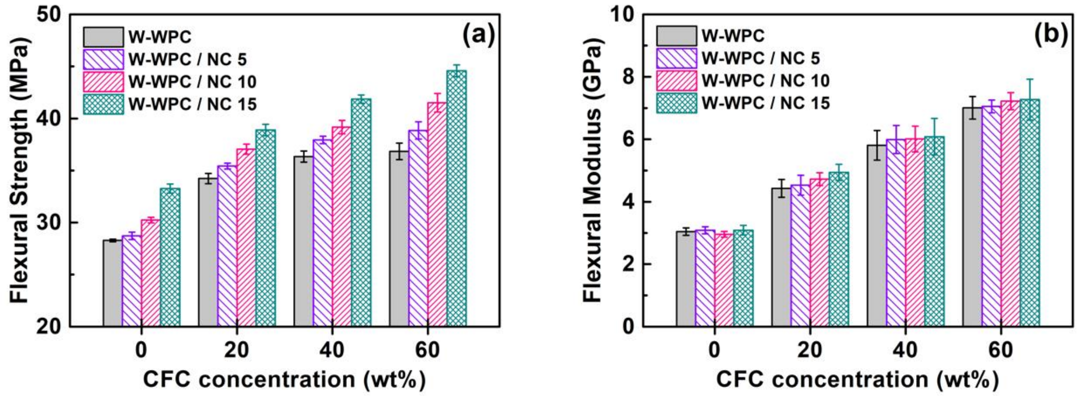

Fig. 5. Flexural properties of recycled WPCs filled with carbon fiber and nanoclay: (a) flexural strength and (b) flexural modulus

The flexural properties of the various recycled WPCs are presented in Fig. 5. The flexural strength improved with increasing incorporation of carbon fiber and nanoclay. This trend was similar to that of tensile strength. The synergistic effect of the orientation of carbon fiber in the longitudinal direction and the platelet-like nanoclay resulted in improved flexural strength (Slonov *et al.* 2018). In addition, the flexural modulus of the composites increased with increasing incorporation of carbon fiber. However, the incorporation of nanoclay did not strongly affect the flexural modulus, which was similar to the effects of carbon fiber and nanoclay on the tensile modulus.

Two-way ANOVA test data on mechanical properties (impact strength, tensile strength, tensile modulus, flexural strength, flexural modulus) are shown in Table 3. The ANOVA results showed that both nanoclay and carbon fiber contents had significant influences on mechanical properties of the recycled WPCs. For the combined effect of nanoclay and carbon fiber contents on the mechanical properties, significant interactions were observed in tensile strength, tensile modulus, and flexural strength at the 95% confidence level. However, in the cases of impact strength and flexural modulus, interactions between nanoclay and carbon fiber contents were not significant.

Table 3. Two-way ANOVA Tests of the Effect of Fillers on Mechanical Properties of Recycled WPCs Filled with Carbon Fiber and Nanoclay

Variables	Mechanical Properties				
	Impact Strength	Tensile Strength	Tensile Modulus	Flexural Strength	Flexural Modulus
Nanoclay	< 0.0001	< 0.0001	0.0001	< 0.0001	0.0031
Carbon Fiber	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Nanoclay × Carbon Fiber	0.4366	< 0.0001	< 0.0001	< 0.0001	0.4252

* The values shown are p-values of 2-way ANOVA tests. The p-values smaller than 0.05 indicate significant influences of the corresponding treatments on mechanical properties at the 95% confidence level.

Thermal Properties

Thermogravimetric (TG) and derivative thermogravimetric (DTG) curves of the various recycled WPCs are presented in Fig. 6. The total TGA results for the various recycled WPCs are summarized in Table 4. The values of T_{95} and T_{50} are the temperatures at which the remaining masses of the composites were 95% and 50%, respectively. The first-stage and second-stage peak maximum temperatures are referred to as T_{Max}^{1} and T_{Max}^{2}, respectively. As the amount of waste WPC decreased and the amount of fillers (carbon fiber and nanoclay) increased, the TG curves shifted to the right, and the T_{95} and T_{50} values also increased. The hybrid incorporation of carbon fiber and nanoclay imparted thermal stability to the composites. Carbon fiber has been reported to be a particularly good filler in terms of thermal properties, and it exhibits greater thermal stability than polypropylene, which was used as the matrix of the composites due to its greater heat-absorption capacity (Rezaei *et al.* 2007). In addition, the dispersed nanoclay acts as a barrier to heat and delays the diffusion of volatile decomposition products into filled composites (Rahman *et al.* 2012).

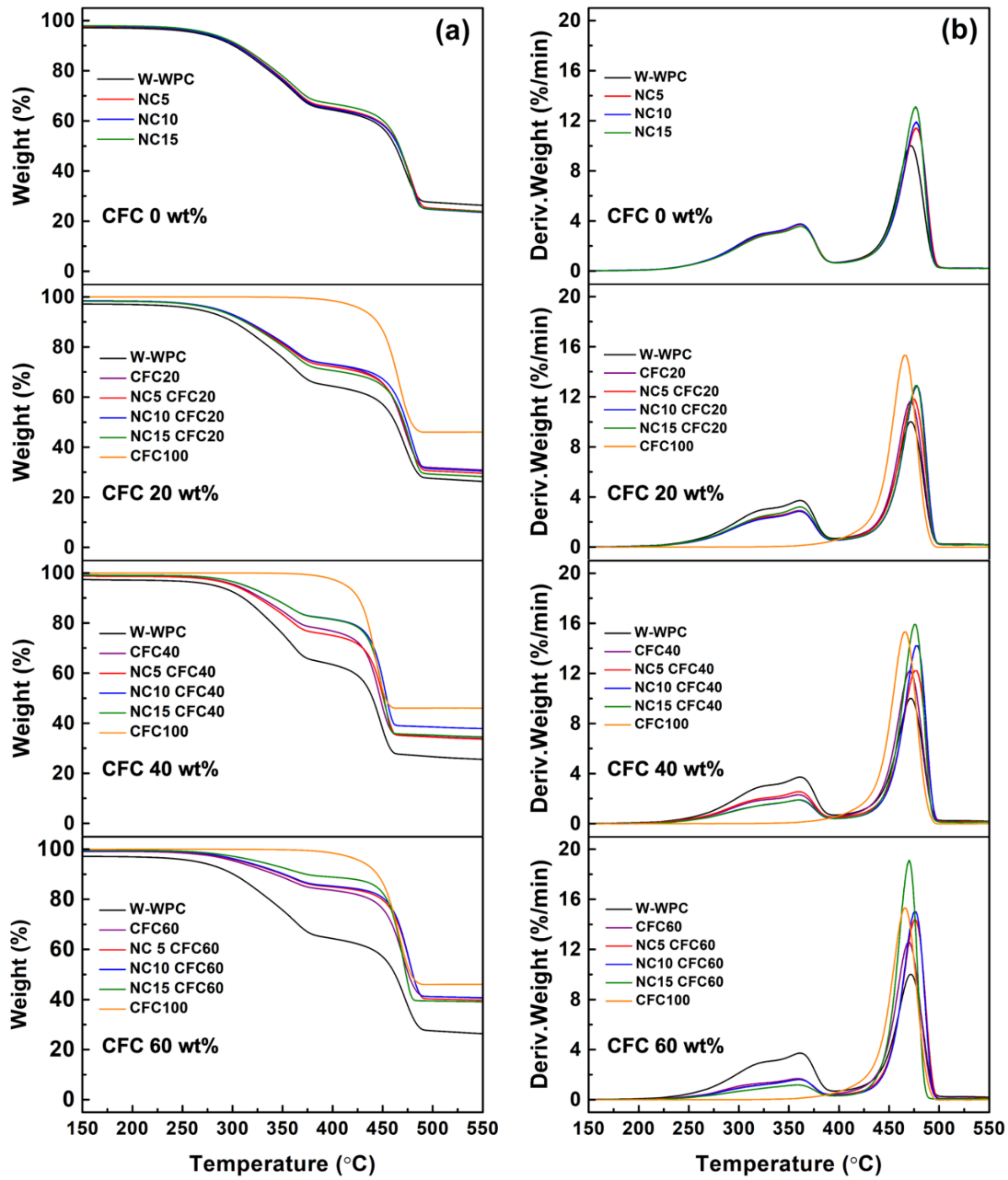

Fig. 6. TGA properties of recycled WPCs filled with carbon fiber and nanoclay: (a) TG curves, (b) DTG curves

The synergistic effect of the fillers (carbon fiber and nanoclay) improved thermal stability. However, the T_{50} of the composite filled with CFC and 15 wt% NC decreased. The incorporation of large amounts of nanoclay can result in agglomeration, which may result in inadequate dispersion of the nanoclay (Rahman *et al.* 2012). Therefore, preventing heat from penetrating into the interior of the composites is difficult. The DTG curves of the composites showed two thermal degradation zones. Whereas the T_{max}^1 in the range of 358 °C to 361 °C was associated with thermal degradation of the wood flour (particularly, cellulose), the T_{max}^2 in the range of 469 °C to 477 °C was related to the thermal degradation of polypropylene. As the amount of waste WPCs decreased, the width of T_{max}^1 decreased. However, the width of T_{max}^2 increased because the thermal degradation behavior of the composites was more strongly influenced by polypropylene than by wood.

Table 4. TGA Results and Water Absorption Properties of Recycled WPCs Filled with Carbon Fiber and Nanoclay

Specimen	TGA Data				Water Absorption Data	
	T_{95} (°C)	T_{50} (°C)	T_{Max}^1 (°C)	T_{Max}^2 (°C)	Max. WA (%)	Max. TS (%)
W-WPC	264.73	462.48	361.06	471.70	13.33 (± 0.09)	6.84 (± 0.44)
NC5	271.82	465.82	361.66	477.18	12.37 (± 0.84)	6.63 (± 0.24)
NC10	272.07	465.86	361.23	477.24	11.62 (± 1.04)	6.60 (± 0.39)
NC15	275.88	466.80	361.61	476.56	7.39 (± 0.25)	6.15 (± 0.36)
CFC20	284.41	469.34	360.50	471.59	10.31 (± 0.13)	6.29 (± 0.36)
NC5 CFC20	284.45	470.58	360.57	474.27	10.19 (± 0.33)	5.78 (± 0.44)
NC10 CFC20	285.46	473.71	360.91	477.67	8.93 (± 0.85)	5.65 (± 0.36)
NC15 CFC20	282.26	471.23	361.13	477.24	7.04 (± 1.39)	5.59 (± 0.16)
CFC 40	292.05	472.02	359.64	470.86	8.44 (± 0.20)	5.13 (± 0.26)
NC5 CFC40	288.99	475.83	360.11	476.56	8.39 (± 0.13)	4.98 (± 0.19)
NC10 CFC40	302.65	480.05	359.76	477.80	7.49 (± 0.43)	4.82 (± 0.14)
NC15 CFC40	303.06	476.58	360.32	475.94	5.48 (± 0.96)	4.73 (± 0.13)
CFC 60	304.17	475.86	358.90	469.6	5.72 (± 0.19)	3.69 (± 0.37)
NC5 CFC60	310.22	480.15	360.04	475.97	5.44 (± 0.13)	3.57 (± 0.27)
NC10 CFC60	312.69	480.30	360.11	476.03	5.28 (± 0.19)	3.51 (± 0.02)
NC15 CFC60	327.22	473.26	358.38	470.04	2.57 (± 0.09)	3.25 (± 0.28)
CFC100	429.30	478.52	-	466.04	1.59 (± 0.24)	1.46 (± 0.29)

* T_{95} (°C), T_{50} (°C): The temperature at which 95% and 50% remaining masses of the composite.
* T_{Max}^1 (°C), T_{Max}^2 (°C): The first-stage peak and second-stage peak maximum temperatures of DTG curves.
* Max. WA (%), Max. TS (%): The maximum water absorption and thickness swelling measured after immersion for 10 weeks.

Electrical Properties

The electrical conductivities of the various recycled WPCs are reported in Table 5. The electrical conductivity of the composites containing 0 wt% of CFC or 20 wt% of CFC could not be measured because the wood flour, other fillers present in W-WPC, and the incorporated nanoclay interfered with the flow of current, which resulted in a resistance too high to be reliably measured. The electrical conductivity of the composites containing 40 wt% of CFC was measurable, and the composites containing 60 wt% of CFC showed enhanced electrical conductivity because of the increased amount of carbon fiber. These results were attributed to the carbon fiber, which is a representative carbon material that maintains current flowability despite the presence of various fibers when it is incorporated into the composites (Yang *et al.* 2015). In addition, the carbon fibers currently used are long, and long carbon fibers enhance electrical conductivity because of their increased longitudinal orientation during the injection molding process. Therefore, the results suggested that incorporating carbon fiber into recycled WPCs enhanced the electrical conductivity of resulting composites. However, composites filled with both carbon fiber and nanoclay exhibited electrical conductivities lower than those of composites without carbon fiber because the nanosized clay interfered with current flow when it was present in the composites.

Table 5. Electrical Conductivity Data for Recycled WPCs Filled with Carbon Fiber and Nanoclay

Specimen	Electrical Conductivity (S/m)
CFC0 and CFC20 Series	N/A
CFC40	7.88×10^{-4} ($\pm$ 0.21×10^{-4})
NC5 CFC40	2.60×10^{-4} ($\pm$ 0.06×10^{-4})
NC15 CFC40	0.43×10^{-4} ($\pm$ 0.01×10^{-4})
CFC60	11.11×10^{-4} ($\pm$ 0.71×10^{-4})
NC5 CFC60	6.52×10^{-4} ($\pm$ 0.18×10^{-4})
NC15 CFC60	5.30×10^{-4} ($\pm$ 0.08×10^{-4})
CFC100	37.63×10^{-4} ($\pm$ 0.36×10^{-4})

Water Absorption Properties

The water absorption properties of the various recycled WPCs are shown in Fig. 7. The maximum water absorption and thickness swelling results for the various recycled WPCs are summarized in Table 4. The CFC100 composite with 50 wt% carbon fiber and 50 wt% polypropylene showed nearly 1% water absorption and thickness swelling behavior. Water absorption has little effect other than moisture penetrating the fine interface between the carbon fiber and the polypropylene (Do *et al.* 2016). As the amount of fillers (carbon fiber and nanoclay) in the composites increased, the absolute amount of waste WPC was reduced; thus, the wood flour present in the waste WPC was also reduced. Because the wood flour has hydrophilic groups, a smaller amount of the wood flour results in a weaker influence on the composite moisture (Gwon *et al.* 2010). However, even when the amount of wood flour was reduced, the composites with only carbon fiber (CFC20, CFC40, and CFC60) exhibited greater water absorption than the composites with both carbon fiber and nanoclay fillers (NC15, CFC20 NC15, and CFC40 NC15). Although the wood flour affects water absorption, the nanoclay in the composites acts as a barrier that delays moisture penetration by creating a tortuous pathway for water molecules to diffuse into the composites (Alamri and Low 2012). Similar trends were observed for the thickness swelling properties. These behaviors were attributed to the fillers (carbon fiber and nanoclay) present in the composites being less affected by water absorption. Therefore, the results suggest that deformation due to moisture can be minimized relative to the deformation of W-WPC, which imparts dimensional stability to the composite.

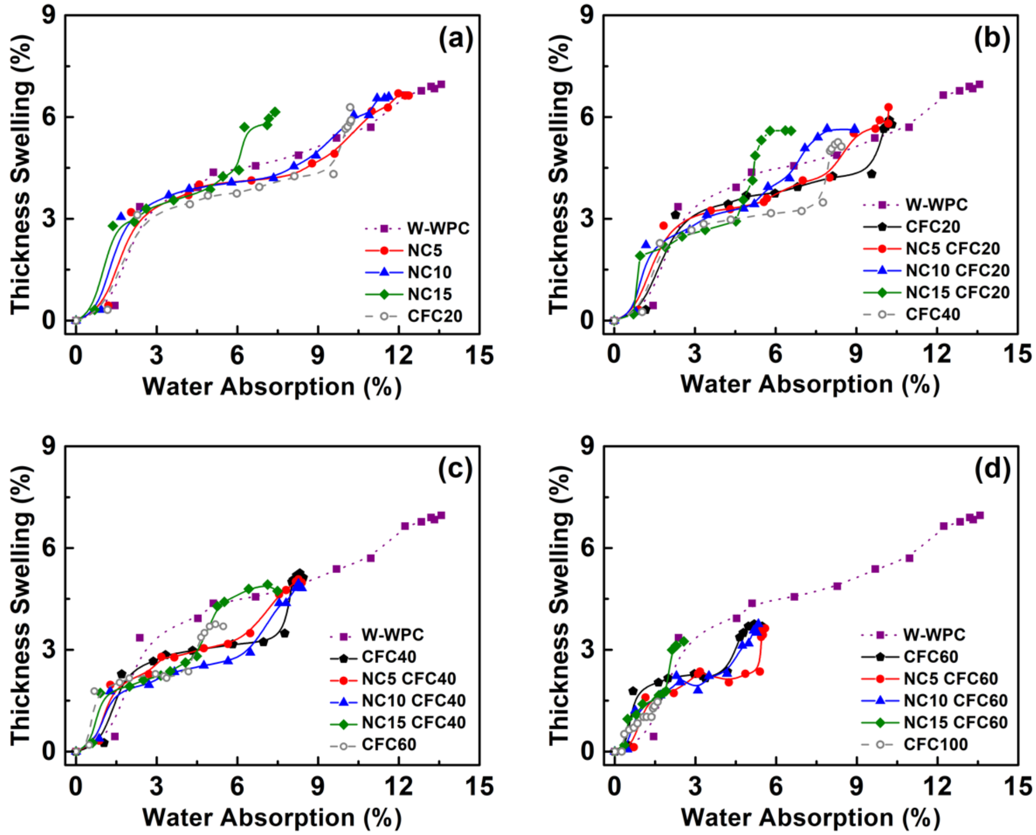

Fig. 7. Water absorption and thickness swelling curves of recycled WPCs filled with carbon fiber and nanoclay: (a) CFC 0 series, (b) CFC 20 series, (c) CFC 40 series, and (d) CFC 60 series

CONCLUSIONS

1. Nanoclay was properly intercalated when added in addition to carbon fiber, and the scanning electron microscopy (SEM) images showed good interfacial bonding between the fillers (carbon fiber and nanoclay) and the polymer matrix.
2. Hybrid incorporation of carbon fiber and nanoclay improved the impact strength, tensile strength, and flexural strength of the resulting composites. However, additional incorporation of nanoclay (more than 5 wt% NC) decreased the impact strength and did not improve the tensile moduli or flexural moduli.
3. The incorporation of the fillers imparted thermal stability when present in the recycled wood-plastic composites (WPCs) and resulted in a synergistic effect when both carbon fiber and nanoclay were present.
4. In terms of water absorption properties, nanoclay slowed water absorption into the composites and resulted in better dimensional stability.
5. Carbon fiber improved the electrical conductivity of recycled WPCs containing various fillers, including wood flour and nanoclay.

ACKNOWLEDGMENTS

This research was carried out with the support of the National Institute of Forest Science (Project No. A2018-0113) and ´R&D Program for Forest Science Technology (Project No. 2019150B10-2023-0301)´ provided by Korea Forest Service(Korea Forestry Promotion Institute).

REFERENCES CITED

Adhikary, K. B., Pang, S. S., and Staiger, M. P. (2008). "Dimensional stability and mechanical behaviour of wood–plastic composites based on recycled and virgin high-density polyethylene (HDPE)," *Composites Part B: Engineering* 39(5), 807-815. DOI: 10.1016/j.compositesb.2007.10.005

Alamri, H., and Low, I. M. (2012). "Effect of water absorption on the mechanical properties of nano-filler reinforced epoxy nanocomposites," *Materials & Design* 42, 214-222. DOI: 10.1016/j.matdes.2012.05.060

Ameli, A., Jung, P. U., and Park, C. B. (2013). "Electrical properties and electromagnetic interference shielding effectiveness of polypropylene/carbon fiber composite foams," *Carbon* 60, 379-391. DOI: 10.1016/j.carbon.2013.04.050

Ataeefard, M., and Moradian, S. (2011). "Polypropylene/organoclay nanocomposites: Effects of clay content on properties," *Polymer-Plastics Technology and Engineering* 50(7), 732-739. DOI: 10.1080/03602559.2010.551438

Bozkurt, E., Kaya, E., and Tanoğlu, M. (2007). "Mechanical and thermal behavior of non-crimp glass fiber reinforced layered clay/epoxy nanocomposites," *Composites Science and Technology* 67(15-16), 3394-3403. DOI: 10.1016/j.compscitech.2007.03.021

Chaharmahali, M., Tajvidi, M., and Najafi, S. K. (2008). "Mechanical properties of wood plastic composite panels made from waste fiberboard and particleboard," *Polymer Composites* 29(6), 606-610. DOI: 10.1002/pc.20434

Chen, L., Wong, S.-C., and Pisharath, S. (2003). "Fracture properties of nanoclay-filled polypropylene," *Journal of Applied Polymer Science* 88(14), 3298-3305. DOI: 10.1002/app.12153

Choi, M. H., Jeon, B. H., and Chung, I. J. (2000). "The effect of coupling agent on electrical and mechanical properties of carbon fiber/phenolic resin composites," *Polymer* 41(9), 3243-3252. DOI: 10.1016/S0032-3861(99)00532-7

Do, V.-T., Nguyen-Tran, H.-D., and Chun, D.-M. (2016). "Effect of polypropylene on the mechanical properties and water absorption of carbon-fiber-reinforced-polyamide-6/polypropylene composite," *Composite Structures* 150, 240-245. DOI: 10.1016/j.compstruct.2016.05.011

Dorigato, A., Pegoretti, A., and Quaresimin, M. (2011). "Thermo-mechanical characterization of epoxy/clay nanocomposites as matrices for carbon/nanoclay/ epoxy laminates," *Materials Science and Engineering: A* 528(19-20), 6324-6333. DOI: 10.1016/j.msea.2011.04.042

Gu, R., Kokta, B. V., Michalkova, D., Dimzoski, B., Fortelny, I., Slouf, M., and Krulis, Z. (2010). "Characteristics of wood-plastic composites reinforced with organo-nanoclays," *Journal of Reinforced Plastics and Composites* 29(24), 3566-3586. DOI: 10.1177/0731684410378543

Gwon, J. G., Lee, S. Y., Chun, S. J., Doh, G. H., and Kim, J. H. (2010). "Effects of chemical treatments of hybrid fillers on the physical and thermal properties of wood plastic composites," *Composites Part A: Applied Science and Manufacturing* 41(10), 1491-1497. DOI: 10.1016/j.compositesa.2010.06.011

Hemmasi, A. H., Khademi-Eslam, H., Talaiepoor, M., Kord, B., and Ghasemi, I. (2010). "Effect of nanoclay on the mechanical and morphological properties of wood polymer nanocomposite," *Journal of Reinforced Plastics and Composites* 29(7), 964-971. DOI: 10.1177/0731684408101790

Iqbal, K., Khan, S.-U., Munir, A., and Kim, J.-K. (2009). "Impact damage resistance of CFRP with nanoclay-filled epoxy matrix," *Composites Science and Technology* 69(11-12), 1949-1957. DOI: 10.1016/j.compscitech.2009.04.016

Kanny, K., Jawahar, P., and Moodley, V. K. (2008). "Mechanical and tribological behavior of clay–polypropylene nanocomposites," *Journal of Materials Science* 43(22), 7230-7238. DOI: 10.1007/s10853-008-2938-x

Khan, S. U., Munir, A., Hussain, R., and Kim, J.-K. (2010). "Fatigue damage behaviors of carbon fiber-reinforced epoxy composites containing nanoclay," *Composites Science and Technology* 70(14), 2077-2085. DOI: 10.1016/j.compscitech.2010.08.004

Khanjanzadeh, H., Tabarsa, T., and Shakeri, A. (2012). "Morphology, dimensional stability and mechanical properties of polypropylene-wood flour composites with and without nanoclay," *Journal of Reinforced Plastics and Composites* 31(5), 341-350. DOI: 10.1177/0731684412438793

Lee, D., Kim, S., Kim, B.-J., Chun, S.-J., Lee, S.-Y., and Wu, Q. (2017). "Effect of nano-CaCO3 and talc on property and weathering performance of PP composites," *International Journal of Polymer Science* 2017, Article ID 4512378. DOI: 10.1155/2017/4512378

Najafi, S. K., Hamidinia, E., and Tajvidi, M. (2006). "Mechanical properties of composites from sawdust and recycled plastics," *Journal of Applied Polymer Science* 100(5), 3641-3645. DOI: 10.1002/app.23159

Rahman, N. A., Hassan, A., Yahya, R., Lafia-Araga, R. A., and Hornsby, P. R. (2012). "Micro-structural, thermal, and mechanical properties of injection-molded glass fiber/nanoclay/polypropylene composites," *Journal of Reinforced Plastics and Composites* 31(4), 269-281. DOI: 10.1177/0731684411435727

Ray, S. S., and Okamoto, M. (2003). "Polymer/layered silicate nanocomposites: A review from preparation to processing," *Progress in Polymer Science* 28(11), 1539-1641. DOI: 10.1016/j.progpolymsci.2003.08.002

Rezaei, F., Yunus, R., Ibrahim, N., and Mahdi, E. (2007). "Effect of fiber loading and fiber length on mechanical and thermal properties of short carbon fiber reinforced polypropylene composite," *Malaysian Journal of Analytical Sciences* 11(1), 181-188.

Seo, Y.-R., Lee, S.-Y., and Kim, B.-J. (2019). "Effects of nanoclay and glass fiber on the microstructural, mechanical, thermal, and water absorption properties of recycled WPCs," *Journal of the Korean Wood Science and Technology* 47(4), 472-485. DOI: 10.5658/WOOD.2019.47.4.472

Slonov, A. L., Zhansitov, A. A., Rzhevskaya, E. V., Khakulova, D. M., Sapaev, K. K., Shetov, R. A., and Khashirova, S. Y. (2018). "Influence of the length and concentration of carbon and glass fibers on the properties of polyphenylene sulfone," *Fibre Chemistry* 50(4), 354-360. DOI: 10.1007/s10692-019-09989-0

Turku, I., and Kärki, T. (2014). "The effect of carbon fibers, glass fibers and nanoclay on wood flour-polypropylene composite properties," *European Journal of Wood and Wood Products* 72(1), 73-79. DOI: 10.1007/s00107-013-0754-8

Unterweger, C., Duchoslav, J., Stifter, D., and Fürst, C. (2015). "Characterization of carbon fiber surfaces and their impact on the mechanical properties of short carbon fiber reinforced polypropylene composites," *Composites Science and Technology* 108, 41-47. DOI: 10.1016/j.compscitech.2015.01.004

Väisänen, T., Haapala, A., Lappalainen, R., and Tomppo, L. (2016). "Utilization of agricultural and forest industry waste and residues in natural fiber-polymer composites: A review," *Waste Management* 54, 62-73. DOI: 10.1016/j.wasman.2016.04.037

Van Hattum, F. W. J., Bernardo, C. A., Finegan, J. C., Tibbetts, G. G., Alig, R. L., and Lake, M. L. (1999). "A study of the thermomechanical properties of carbon fiber-polypropylene composites," *Polymer Composites* 20(5), 683-688. DOI: 10.1002/Pc.10391

Wolcott, M. P., and Englund, K. (1999). "A technology review of wood-plastic composites," in: *Proceedings of 33rd International Particleboard/Composite Materials Symposium*, Pullman, WA, USA, pp. 103-111.

Yang, H., Gong, J., Wen, X., Xue, J., Chen, Q., Jiang, Z., Tian, N., and Tang, T. (2015). "Effect of carbon black on improving thermal stability, flame retardancy and electrical conductivity of polypropylene/carbon fiber composites," *Composites Science and Technology* 113, 31-37. DOI: 10.1016/j.compscitech.2015.03.013

Yasmin, A., Luo, J. J., Abot, J. L., and Daniel, I. M. (2006). "Mechanical and thermal behavior of clay/epoxy nanocomposites," *Composites Science and Technology* 66(14), 2415-2422. DOI: 10.1016/j.compscitech.2006.03.011

Zhou, Z., Xu, M., Yang, Z., Li, X., and Shao, D. (2014). "Effect of maleic anhydride grafted polyethylene on the properties of chopped carbon fiber/wood plastic composites," *Journal of Reinforced Plastics and Composites* 33(13), 1216-1225. DOI: 10.1177/0731684414531633

Article submitted: February 28, 2020; Peer review completed: June 13, 2020; Revised version received and accepted: August 15, 2020; Published: August 24, 2020.
DOI: 10.15376/biores.15.4.7671-7686