Screw Withdrawal Resistance and Surface Roughness of Woven Carbon and Glass Fiber-reinforced Wood-plastic Composites

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Wood-plastic composites (WPCs) have become one of the most remarkable materials for construction in recent years. Along with high resistance against biological threats, the high mechanical properties are also desired from WPCs as well. In this study, polypropylene (PP) and polyethylene (HDPE) based flat-pressed WPC specimens were reinforced with woven fiber fabric to gain higher mechanical properties. Woven fabrics were located 20% (w/w) below for both surfaces. Carbon fiber and glass fiber woven fabrics, known to have high mechanical properties, were preferred to improve screw withdrawal resistance (SWR) of WPC. Specimens were produced with different wood flour contents (40, 50, and 60%). Results indicated that the increase of SWR reached up to 83%. The highest increase was obtained from carbon fiber for PP, while it was glass fiber for HDPE fabric. The coupling agents had a positive effect on SWR. This study also showed that PE based WPCs had higher SWR compared to PP based ones. Moreover, as wood flour content increased, SWR decreased. The surface roughness of WPCs was also investigated. Contrary to SWR, the wood flour content positively affected the surface roughness; *i.e.*, as wood content increased, surface roughness of WPCs increased. The structure of specimens were also examined using SEM.

Keywords: Wood-plastic composites; Reinforcement; Screw resistance; Surface roughness

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INTRODUCTION

Wood-plastic composites (WPCs) have drawn much attention in recent years. Their application areas gradually increase with the passage of time. The applications of WPCs starting with nonstructural areas (decking, railing, fencing, timber, sidings, benches, window door frames, and indoor furniture) currently range from construction to the automotive industry (Stark and Matuna 2007; Kim and Pal 2010; Najafi 2013). The demand for new materials has made WPCs competitive with other structural materials. Especially, the increase in demand for natural products has significantly contributed to WPC production.

The combination of lignocellulosic materials, thermoplastic resins, and additives has brought in unique features to new material, referred to as WPC. The low cost, low density (compared to other composites), easy manufacturing process, low maintenance, and usability of recycled materials are just a few advantages of WPCs (Klyosov 2007). However, there are also some disadvantages.

Because wood is a natural substance, it is a renewable and accessible material in nature (Schmidt 2006). However, it can be degraded under favorable conditions by fungi, insects, and microorganisms. Moreover, it changes its dimensions depending on environmental humidity. Above all, it can be negatively affected by outdoor conditions (ultraviolet radiation, rain, humidity, and gases, *etc*.). To overcome some of the negative properties of wood and thermoplastics, the composites have been reinforced with different synthetic fibers such as carbon fiber, glass fiber, *etc*.

Such reinforcement has been shown to improve WPC's mechanical properties as well as thermal properties and weathering resistance (Klyosov 2007). Investigations related to reinforcement of thermoplastics with carbon as well as glass fiber have also increased recently (Fu *et al*. 1999, 2000; Rezaei *et al*. 2008; Karsli and Aytac 2013). According to these studies, reinforcement with glass and carbon fiber increases mechanical properties of composites by up to 100%. Moreover, carbon fiber increases degradation temperature of composites due to its heat absorption capacity (Rezaei *et al*. 2008, 2009; Kaymakci *et al*. 2017). Some studies have even argued that woven fabrics increase mechanical properties up to 500% (Russo *et al*. 2013; Simeoli *et al*. 2014; Sorrentino *et al*. 2015; Boccardi *et al*. 2016).

Surface roughness is an important parameter to determine the surface quality of composites. The adhesion between surface and coating materials is crucial for the surface modification such as coatings, overlaying, wood veneer sheet, *etc*. (Ayrilmis *et al*. 2012). The decrease in wood flour content and particle size increase smoothest surface (Ayrilmis *et al*. 2012; Jeamtrakull *et al*. 2012). Melt flow index of the polymer also affects surface quality (Gurau and Ayrilmis 2019). In recent years, radiation-based surface modification methods have been used to be improved wettability and surface energy as well as decreasing surface roughness (Yáñez-Pacios and Martín-Martínez 2018).

Wood-plastic composite panels must be joined with fasteners to form a unity in the structure. Mechanical fasteners (screws, nails, *etc*.) are the most appropriate joining methods for WPCs (Haftkhani *et al*. 2011). The stability of structure depends on the performance of the fasteners (Ghanbari *et al*. 2014). Therefore, the relation between fasteners and WPCs has to be well-understood as well as detailed and compatible design. The fiber type, fiber content, fiber size, and blending methods also have influence on fastener withdrawal resistance (Ghambari *et al*. 2013). The highest withdrawal strength has been obtained from larger wood fiber sizes. Ayrilmis and Jarusombuti (2011) found that as wood flour content increases, the SWR decreases. Additionally, the addition of a coupling agent also increases SWR. Ilce *et al*. (2015) stated that the increase in the numbers of layers decreased the SWR of wood plastic laminate.

Carbon and glass fibers are recognized as materials associated with high mechanical properties. The aim of this study was to combine the high mechanical properties of carbon and glass woven fiber fabrics with WPC's. There have been a limited number of studies about the performance of fasteners on WPCs. In this study, the screw withdrawal performance of reinforced WPC's was investigated with various parameters, including wood flour content (40, 50, and 60 w/w%), thermoplastic polymers (polypropylene and polyethylene), woven fiber fabric types (carbon and glass fiber), woven fiber fabric density (~ 200 g/m^2 and ~ 400 g/m^2), and coupling agents. The surface of WPCs was characterized *via* determination of surface roughness. The homogeneity of WPC specimen structure was also investigated using scanning electron microscope (SEM).

EXPERIMENTAL

Materials

As a softwood species, pine wood (*Pinus sylvestris* L.) flour (40- to 60-mesh sizes) was supplied from a commercial supplier in Turkey (Marmara Wood Shaving, Istanbul, Turkey).

Two different thermoplastic polymers were used as the matrix. High-density polyethylene (HDPE) and polypropylene (PP) were provided in powder form from a commercial supplier in Turkey (Ucar Plastic, Izmir, Turkey). The HDPE has a melt flow index (MFI) of 5.5 g/10 min (190 °C/2.16 kg), and a density of 0.965 g/cm^3, while PP has a MFI of 3 to 27 g/10 min (190 °C/2.16 kg), and a density of 0.905 g/cm^3. Maleated anhydride grafted polyethylene (MAPE) and maleated anhydride grafted polypropylene (MAPP) were used as coupling agents (Zirve Polymer, Istanbul, Turkey). The MAPE has an MFI of 1 to 4 g/10 min (190 °C/2.16 kg), and a density of 0.92 g/cm^3, while PP has a MFI of 40 to 80 g/10 min (190 °C/2.16 kg), and a density of 0.92 g/cm^3.

Two different woven fabrics (carbon and glass fiber) were utilized. A twin weave-type woven fabric (E-type glass fiber) with a specific mass of 195 g/m^2 and 390 g/m^2 for glass fiber (GF) (SPM Composites, Ankara, Turkey), a twin weave-type woven fabric with a specific mass of 200 g/m^2 and 400 g/m^2 for carbon fiber (CF) (SPM Composites, Ankara, Turkey) were used as reinforcement.

Methods

Wood flour was oven-dried at a temperature of 70 °C until less than 2% moisture content was reached. Three different wood flour and thermoplastic ratios (40:60, 50:50, and 60:40 (w/w)) were tested. Wood flour/thermoplastic polymer was pre-mixed with or without coupling agent with 3% w/w of MAPP or MAPE with mechanical blender (1200 rev/min). Then mixture was mixed in a rotary drum blender (30-40 rev/min) for 5 min. Following the blending, the mixture was weighed. Then, the 20% of the mixture was formed into wax paper on an aluminum caul plate with a forming box, and the woven fabric was laid on the mixture. Next, 60% of the mixture was formed on the first sheet of woven fabric and then the second woven fabric was laid on the mixture. Finally, the rest of the mixture (20%) was formed (Fig. 1). The mat was hot-pressed for 15 min (CemilUsta SSP 125, Istanbul, Turkey). Thereafter, the board was left in the hot-press for cooling. The target density of the board was 1 g/cm^3. The pressing pressure was 2.3 to 2.5 N/mm^2, and the temperature was 170 °C. In total, 180 test panels, three for each type of panel, were manufactured. The panel size was 500 mm × 500 mm × 4 mm. Test panels were conditioned according to the ASTM D618 (2000).

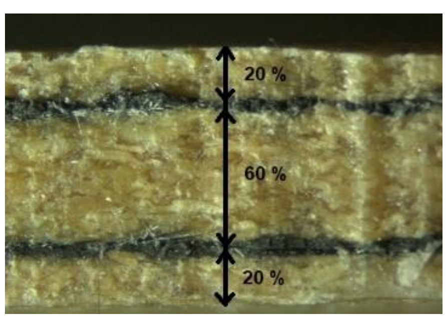

Fig. 1. Laying of woven fabric and production process

Screw withdrawal strength was determined according to the ASTM D1037 (2006) standard. A universal testing machine (Marestek, Istanbul, Turkey) was used to determine the withdrawal strength of screws in the test samples with dimensions of 50 mm × 50 mm × 4 mm. The pilot hole diameter for each screw was 2.7 mm. The screw diameter of 4.2 mm and length of 38 mm was used in this study. The thread pitch of screw was 1.4 mm. The screws were hand-driven 15 ± 0.5 mm into the test samples. Nine samples for each group, a total of 540 samples were tested. The maximum holding strength was then divided by the panel thickness, and the results were recorded as N/mm.

A Mitutoya SurfTest SJ-301 (Mitutoyo Corporation, Kanagawa, Japan) instrument was employed for surface roughness measurements. The R_a and R_z roughness parameters were measured to evaluate the surface roughness of the panel according to DIN 4768 (1990). R_a is the arithmetic mean of the absolute values of the profile departures within the reference length, and R_z is the arithmetic mean of the 4-point height of irregularities. In surface roughness measurements, the cut-off length was 2.5 mm, the sampling length was 12.5 mm, and the detector tip radius was 10 μm.

The SEM analysis of WPC's was conducted with a Jeol (JSM-7600F, USA) instrument. Before investigation, samples were oven-dried and gold coated (Emitech K550X, Kent, UK).

The variance analysis (SPSS, IBM Corporation, Version 22, Armonk, NY, USA) was performed at an α level of 0.05 to determine the differences between the main factors of fiber type, wood flour content, coupling agent, and plastic type.

RESULTS AND DISCUSSION

Scanning Electron Microscopy (SEM)

The homogeneous mixture of polymer and wood flour influences the mechanical properties of WPC. Moreover, the integration of woven fabric with matrix is key point to obtain high mechanical properties. The homogeneity of the components of WPC was investigated by SEM. Wood flour and polymer were uniformly mixed, as seen in Fig. 2. Wood flour was not aggregated in the polymer, which indicates a homogeneous matrix. Meanwhile, there were no gaps in the matrix. Glass and carbon fiber fabrics were well-integrated with matrix. It was clearly seen that the polymers penetrated the woven fabrics. Consequently, the good integration between matrix and fabrics explains high SWR of specimens.

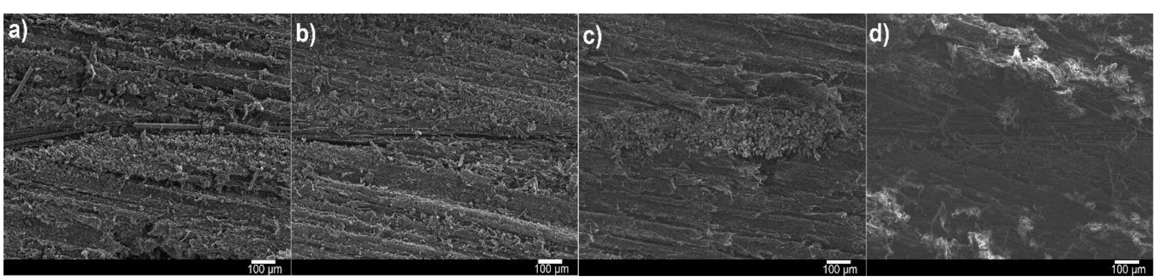

Fig. 2. SEM images of reinforced WPC's (50% wood flour): a) 390 gr/m² GF for PP; b) 200 gr/m² CF for PP; c) 390 gr/m² GF for HDPE; d) 200 gr/m² CF for HDPE

Screw Withdrawal Resistance

The effect of reinforcement of WPC with woven fabrics on the SWR was investigated. The SWR results are given in Table 1. The SWR values ranged from 67.8 to 177.0 N/mm. Results indicated that the SWR was increased over 80% compared to the control samples. Reinforcement increased SWR up to 82.3% for PP, while it was up to 62.6% for HDPE.

Table 1. Screw Withdrawal Strength of WPC Reinforced with Woven Fiber Fabric

Woven Fabric Type	Wood Flour/Thermoplastic Ratio	Coupling Agent	Screw Withdrawal Strength (N/mm)	
			PP	HDPE
Control	40/60	Not included	77.38 (5.80)	108.90 (6.91)
		Included	91.64 (7.59)	124.83 (4.93)
	50/50	Not included	74.69 (3.89)	100.93 (6.68)
		Included	88.70 (7.36)	124.65 (5.85)
	60/40	Not included	67.84 (5.31)	88.42 (6.64)
		Included	78.76 (4.86)	101.08 (5.63)
Glass fiber (195 g/m^2)	40/60	Not included	108.20 (5.98)	139.42 (3.21)
		Included	119.55 (8.48)	159.78 (8.63)
	50/50	Not included	96.87 (8.83)	128.08 (4.14)
		Included	119.31 (7.30)	139.26 (10.66)
	60/40	Not included	92.11 (5.69)	98.66 (6.45)
		Included	102.30 (8.91)	125.17 (6.69)
Glass fiber (390 g/m^2)	40/60	Not included	115.64 (6.34)	165.58 (10.50)
		Included	140.96 (10.05)	177.04 (9.83)
	50/50	Not included	108.49 (7.86)	158.45 (5.40)
		Included	133.28 (7.92)	171.33 (12.19)
	60/40	Not included	96.79 (7.69)	126.83 (7.66)
		Included	121.50 (5.66)	144.59 (9.18)
Carbon fiber (200 g/m^2)	40/60	Not included	133.02 (9.71)	151.40 (3.67)
		Included	141.08 (4.08)	155.60 (6.72)
	50/50	Not included	123.85 (9.56)	130.82 (7.77)
		Included	132.09 (9.45)	142.65 (6.68)
	60/40	Not included	110.11 (7.20)	126.14 (8.58)
		Included	115.37 (8.64)	127.44 (4.70)
Carbon fiber (400 g/m^2)	40/60	Not included	125.36 (11.44)	121.75 (6.64)
		Included	126.67 (10.39)	133.58 (4.35)
	50/50	Not included	116.72 (6.45)	100.31 (7.61)
		Included	124.19 (9.56)	106.39 (3.55)
	60/40	Not included	107.19 (6.52)	74.24 (5.45)
		Included	118.46 (8.70)	88.08 (4.63)

Note: Values in the parentheses are standard deviations

According to the multivariate analysis of variance test, the effects of fiber type, wood flour, coupling agent, and plastic type, which are the main factors on the screw withdrawal strength, were statistically significant, as shown in Table 2. The highest SWR was obtained from the WPC based on HDPE. The coupling agent, which increased internal bonding capacity between compounds, had a remarkable effect on SWR, as shown by others (Madhoushi *et al*. 2009; Ayrilmis and Jarusombuti 2011). The influence of wood flour content on SWR is considerable. As wood flour content increased, SWR decreased (Ayrilmis and Jarusombuti 2011; Chavooshi *et al*. 2013, 2014; Ghanbari *et al*. 2014). The incompatibility between hydrophilic lignocellulosic materials and hydrophobic thermoplastic has been shown to result in decreased mechanical properties (Kim and Pal 2010). Valente *et al*. (2011) stated that wood flour content up to 35% does not significantly affect SWR. Chaharmahali *et al*. (2008) highlighted that the SWR of WPCs containing wood flour content up to 60% is higher than other wood-based composites. The finding of this study is parallel to findings of the current literature. The SWR results of specimens containing wood flour content 40 to 50% were somewhat similar. However, the difference in the SWR results was with specimens containing 60% wood flour content.

Table 2. Results of Multivariate Analysis of Variance Test for Screw Withdrawal Strength of WPC Reinforced with Woven Fiber Fabric ($p < 0.05$)

Source	Sum of Squares	df	Mean Square	F	p-value
Woven fabric type (WFT)	133119.436	4	33279.859	533.733	0.000
Wood/Plastic content (WC)	58656.224	2	29328.112	470.356	0.000
Coupling agent (CA)	24182.880	1	24182.880	387.838	0.000
Plastic type (PT)	42595.763	1	42595.763	683.139	0.000

The woven fabric type was also an important factor for SWR results. As seen in Table 1, carbon fiber gave the best results with PP, while the best results were obtained with glass fiber in the case of HDPE. However, high density carbon fiber woven fabric (400 g/m^2) remained incapable of developing high SWR. It was thought that as the weight per square meter increases, the thickness of fabric might increase so that the mixture of thermoplastic/wood flour cannot penetrate easily. However, the same situation was not valid for glass fiber woven fabric, especially 390 g/m^2. It is worth noting that the production method and structure was different for both woven fabrics. Therefore, the thickness and closeness (mesh size) of fabric were not similar. As a result of this, carbon fiber woven fabric revealed an adverse effect for 400 g/m^2.

Surface Roughness

Surface roughness is an important variable that has an effect on the grading, quality, gluing, and coating of panels (Aydın and Colakoglu 2003). The bonding performance is directly affected by the surface characteristics of a WPC, which is similar to that of wood (Oporto *et al*. 2007). Physical interlocking mechanically contributes to the integration of two surfaces (Niska and Sain 2008). Therefore, the surface roughness positively affects physical interlocking as a result of increased surface area of bonding materials (Ayrilmis and Jarusombuti 2011).

According to the multivariate analysis of variance test, the effects of wood flour, coupling agent, and plastic type, which are the main factors associated with R_a values, were statistically significant, as shown in Table 3. On the other hand, as expected, fiber type did not have a significant effect on surface roughness values. The surface roughness values of the specimens are also given in Table 4. As shown, the increase in wood flour content increased the surface roughness. The incompatibility between wood and thermoplastic polymers had a negative effect on surface roughness as well as mechanical properties. Jeamtrakull *et al.* (2012) stated that the wood type does not has an influence on surface roughness while the wood flour content has a significant effect. The specimens containing coupling agents had an improved surface quality. The use of a coupling agent also resulted in a relatively smoother surface while increased wood flour content causes a rougher surface (Jarusombuti and Ayrilmis 2011).

Table 3. Results of Multivariate Analysis of Variance Test for R_a ($p < 0.05$)

Source	Sum of Squares	df	Mean Square	F	p-value
Woven fabric type (WFT)	21.482	4	5.371	1.750	0.51
Wood/Plastic content (WC)	91.678	2	45.839	14.939	0.000
Coupling agent (CA)	44.202	1	44.202	14.405	0.000
Plastic type (PT)	288.083	1	288.083	93.887	0.000

Table 4. Surface Roughness of WPC Reinforced with Woven Fiber Fabric (μm)

Woven Fabric Type	Wood Flour/Thermoplastic Ratio	Coupling Agent	Surface Roughness (μm)					
			PP			HDPE		
			Ra	Rz	Ry	Ra	Rz	Ry
Control	40/60	Not included	9.08	47.43	67.66	3.25	17.91	22.35
		Included	4.17	47.49	61.25	1.71	11.59	16.88
	50/50	Not included	11.06	66.22	15.84	3.28	18.63	24.47
		Included	5.49	48.24	74.51	2.38	15.25	18.70
	60/40	Not included	11.12	67.35	113.18	6.04	36.06	46.53
		Included	7.63	55.32	84.06	5.38	30.75	40.40
Glass fiber (195 g/m^2)	40/60	Not included	5.59	41.20	65.35	2.73	15.52	20.75
		Included	3.27	20.96	32.07	4.12	22.60	28.90
	50/50	Not included	5.59	50.82	83.51	3.44	19.25	26.22
		Included	4.87	28.85	44.18	4.18	23.19	29.72
	60/40	Not included	6.74	58.68	101.78	3.60	20.38	28.78
		Included	6.72	42.42	63.48	4.58	27.10	41.91
Fiber glass (390 g/m^2)	40/60	Not included	6.28	29.83	64.51	2.95	15.95	18.16
		Included	5.99	18.13	29.08	3.04	17.49	26.17
	50/50	Not included	9.82	57.51	66.66	3.50	18.16	21.75
		Included	6.17	42.45	78.56	3.64	25.15	34.53
	60/40	Not included	10.06	67.98	93.20	3.85	26.18	64.73
		Included	7.06	46.77	105.79	4.93	27.62	53.51
Carbon fiber (200 g/m^2)	40/60	Not included	5.12	39.24	86.36	3.38	22.00	36.26
		Included	4.00	27.34	45.45	3.66	20.80	24.71
	50/50	Not included	9.86	59.79	107.01	3.68	22.18	40.47
		Included	4.17	27.57	52.20	3.99	22.83	28.24
	60/40	Not included	10.94	66.44	107.99	4.36	26.09	47.30
		Included	5.80	37.43	61.59	4.39	23.25	38.62
Carbon fiber (400 g/m^2)	40/60	Not included	4.82	27.15	60.06	2.77	18.49	25.25
		Included	5.79	35.63	54.44	3.09	17.49	19.29
	50/50	Not included	8.16	46.99	103.21	3.84	24.63	40.28
		Included	6.17	36.87	70.53	4.04	22.07	29.14
	60/40	Not included	8.37	49.27	131.20	4.80	26.78	49.54
		Included	6.44	45.52	98.10	4.79	33.30	57.47

CONCLUSIONS

1. The fiber type, wood flour content, thermoplastic polymer type, and coupling agents had a significant effect on screw withdrawal resistance (SWR).
2. Over 80% increase in SWR was achieved with fiber reinforcement in comparison with the absence of fiber reinforcement. Up to 50% wood flour content did not significantly affect the SWR.

3. Coupling agents increased the compatibility between the substances, thus increased SWR results of specimens.
4. The woven fabric fiber type also was an important parameter for SWR. The carbon (200 m^2) and glass fiber (390 g/m^2) woven fabric gave the best results.
5. As wood flour content increased, the surface roughness increased. Meanwhile, the use of a coupling agent also resulted in a relatively smoother surface.
6. Scanning electron microscopy (SEM) results indicated that homogeneous blending and uniform layering in mat structure was achieved; however, penetration of substances into 400 g/m^2 fiber was not successful which adversely affects mechanical performance of WPC panels.

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