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The Effect of Chopped Glass and Carbon Fiber Reinforcement on Physical, Mechanical, and Fire Performance of Wood Plastic Composites

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Wood plastic composites are among the most popular engineering materials, used as deck materials as well as in construction. To improve the properties of wood plastic composites, they are reinforced with various materials. This study investigates the synergic effect of glass fiber and carbon fiber reinforcement on wood plastic composites regarding their physical, mechanical, and fire resistance performance. The reinforcement materials significantly limited the water absorption due to their hydrophobic nature. The reinforcement fibers acted as a barrier against water and limited the uptake although the water absorption and thickness swelling values increased with exposure time. Moreover, the high strength of the reinforcement fibers improved the modulus of elasticity up to 122% and 41% for the flexural strength. Additionally, the long glass fibers significantly contributed to improving the tensile strength, which indicates that fiber length is essential. The scanning electron microscope micrographs revealed that the carbon fibers had a rougher surface than the glass fibers, proving their higher resistance to stress. The observed gaps were also evidence of poor adhesion between the matrix and the fibers. On the other hand, the carbon fibers and long glass fibers positively affected the load transfer in the matrix. Unfortunately, the fiber reinforcement has only a slight effect on the fire resistance performance. Furthermore, the improvement in the limit oxygen index test values was limited. However, the reinforcement fibers exhibit a barrier effect, inhibiting dropping, which is crucial for structural integrity.

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Introduction

Wood plastic composites (WPCs) are wood-based composites that are superior to pure wood, and polymer materials. Therefore, they are used in the production of many parts of products such as furniture to construction nowadays, while the first use of WPCs was as a deck material. However, its weaknesses such as humidity, result in dimensional instability, which induces breakage of the polymer layer on the wood fiber, limiting the usage of WPCs in many areas [Altgen and Rautkari 2021; Martikka et al. 2019; Rowell 2012]. Moreover, structural damage is exacerbated by UV light, temperature, rain, and other outdoor conditions [Fabiyi and McDonald 2010]. The low creep resistance of polymer also restricts the applications of WPCs [Wang et al. 2015].

Similar to wood-based composites, plastic-based composites are no longer employed in conventional usage areas, for example, railway ties, bridges, or marine constructions where improved properties are an obligation, not a need [Bajracharya et al. 2014]. Combining materials such as wood flour (WF) and plastic is insufficient to improve the properties in some usage areas. Moreover, reinforcements may be necessary for materials to obtain better properties. Reinforcement fibers such as basalt, glass, and carbon are commonly employed as reinforcement materials in various industries [Ashori 2008]. Glass fibers (GF) are added to thermosetting resins to improve the mechanical properties of parts of high-quality cars [Wu et al. 2018]. Carbon fibers (CF) are used in the aerospace industry as well as in construction [Aamir et al. 2019]. Similarly, the construction industry benefits from basalt fibers (BF) to obtain earthquake-resistant structures [Anandamurthy et al. 2017].

The main reason why these fibers are the favorite reinforcements is their high physical, mechanical, and thermal properties. Due to having high degradation temperatures (above 1000°C), they behave as a thermal shield, which enables heat to be equally distributed in the materials, retarding their degradation. The reinforcement improved the hardness of the composites due to the high stiffness of the fibers.. Moreover, the reinforcement provides better structural integrity, enabling composites to transfer better load. Therefore, this results in enhanced mechanical properties [Kada et al. 2016]. Guo and Kethinene [2019] found that the tensile strength of polypropylene (PP) based WPCs produced by direct injection methods improved by up to 30% and 38% for GF and CF, respectively, while it was 26% and 78% for the tensile modulus. The reinforcement also restrained the dripping of plastic. Guan et al. [2021] stated that although straw powder decreased the mechanical properties of WPCs, CF reinforcement improved the tensile strength up to 21%, while it was 27% for the bending strength.

As mentioned above, there are many studies on GF and CF-reinforced WPCs. Nonetheless, there are limited studies related to the synergic effect of GF and CF. The combination of GF and CF could offer composites superior properties . The primary aim of this study is to improve the physical, mechanical, and fire resistance performance of high-density polyethylene-based WPCs by exploiting the synergic effect of fiber lengths and fiber ratio of chopped GF and CF to widen the application of WPCs, such as in construction.

Materials and methods

1. Materials

High-density polyethylene (HDPE) and pine wood flour (WF) (40-60 mesh) (*Pinus sylvestris* L.) (Turkey) were utilized to produce the WPCs. The fine-grain form of HDPE (200 mesh) was provided by Ucar Plastik (İzmir, Turkey) with a density of 0.965 g/cm^3 and a melt flow index (MFI) of 5.5 g/10 min (190ºC/2.16 kg). GF and CF were used as the reinforcement. 4 mm and 10 mm fiber lengths with 11 μm filament diameters were selected for E-GF, while the CF had a 6 mm fiber length and a bulk density of 600g/l. Maleic anhydride grafted polyethylene (MAPE) (Licocene PE MA 4351 Fine Grain) with a density of 0.99 g/cm^3 and a softening point of 123°C was added to the matrix to improve the binding of the materials.

2. WPCs production

The WF was oven-dried until the moisture content was below 2%. The mixture of WF, polymer, chopped GF, and/or CF was prepared according to Table 1. A single screw extruder (Teknomatik, Turkey) was utilized to obtain a homogenous mixture. The temperature was set at 180, 185, 190, and 195°C. The extruder screw speed was 40 rpm. The extruded samples were cooled in water and pelletized. The pellets were dried and compressed in a hot press (CemilUsta SSP 125, Istanbul, Turkey) with a 24-26 kg/cm^2 pressure for 15 min at 180°C to obtain 500 mm x 500 mm x 4 mm panels. After production, the panels were conditioned according to ASTM D618-21.

3. Water absorption (WA) and thickness swelling (TS)

The samples of the dimensions 50 mm x 50 mm x 4 mm were immersed in water (20± 1°C) for 672 h. The test was performed according to ASTM D570:98 [2018] standards. Five samples were tested for each group.

4. Mechanical properties

The flexural strength (FS), modulus of elasticity (MOE), and tensile strength were determined utilizing a universal test machine (Marestek, Istanbul, Turkey) according to ASTM D790-17 [2017] and ASTM D638-14 [2014] standards. Eight specimens 127 mm x 12.7 mm x 4 mm were tested for flexural strength, while dog bone shape specimens were used to ascertain the tensile strength.

Table 1. Ratios of components for WPC production

Groups	Wood flour (%)	HDPE (%)	MAPE (%)	Short glass fiber (%)	Long glass fiber (%)	Carbon fiber (%)
Neat-HDPE	-	98	2	-	-	-
Control	40	58	2	-	-	-
SGF5	40	53	2	5	-	-
SGF10	40	48	2	10	-	-
LGF5	40	53	2	-	5	-
LGF10	40	48	2	-	10	-
CF5	40	53	2	-	-	5
CF10	40	48	2	-	-	10
MIX5	40	53	2	5/3	5/3	5/3
MIX10	40	48	2	10/3	10/3	10/3

5. Limit oxygen index (LOI) test

The minimum oxygen content for combustion of the samples was determined by the LOI test according to ASTM D2863-19 [2019] standards. Specimens with the dimensions 127 mm x 12.7 mm x 4 mm were burned in a glass column of a Dynisco Limiting Oxygen Index Chamber (Franklin, USA). Five samples were tested for each group.

6. Microscopic examination

The WPC samples were oven-dried and gold-coated (Emitech, SC7620, France). Scanning electron microscope (SEM) examinations were conducted with a Zeiss Evo LS10 (Germany) device.

7. Statistical analysis

Statistical analysis was performed to examine the data according to the analysis of variance (one-way ANOVA) with the Duncan test ($p < 0.05$).

Results and discussion

1. Physical properties

The effect of GF and CF reinforcement on the physical properties of WPCs was investigated, as seen in Table 2. The WA and TS values grew with increasing exposure time. Wood is a hydrophilic material, which easily bonds with water molecules, which and changes its dimensions [Ayrilmis et al. 2011; Rahman et al. 2018; Shalbafan et al. 2013]. Therefore, the WF negatively affected the WA and TS values. Nevertheless, the reinforcement restricted WA and TS. Turku and Kärki [2014] investigated the water absorption of hybrid composites reinforced with GF and CF, which were found to be lower than the control samples due to decreasing the amount of WF as well as the barrier effect as the surface of GF could interact with water molecules, while CF has a hydrophobic character.

Table 2. WA and TS values of WPCs

Groups	WA (%)					TS (%)				
	24 h	72 h	168 h	336 h	672 h	24 h	72 h	168 h	336 h	672 h
Neat HDPE	0.22^{a} (0.11)	0.59^{a} (0.25)	0.62^{a} (0.24)	0.78^{a} (0.14)	0.95^{a} (0.13)	0.77^{a} (0.15)	1.30^{a} (0.88)	1.54^{a} (0.28)	1.82^{a} (0.33)	1.90^{a} (0.42)
Control	3.95^{d} (0.13)	7.64^{e} (0.11)	12.41^{e} (0.23)	15.80^{f} (0.16)	22.49^{g} (0.47)	5.01^{b} (1.00)	9.33^{d} (1.27)	13.11^{d} (1.61)	16.96^{d} (2.01)	21.57^{c} (2.78)
SGF5	0.47^{b} (0.07)	1.12^{c} (0.15)	1.61^{c} (0.04)	2.49^{d} (0.08)	3.65^{e} (0.08)	1.36^{a} (0.90)	2.86^{bc} (0.71)	3.15^{bc} (0.86)	3.43^{abc} (1.12)	4.22^{b} (1.26)
SGF10	0.64^{c} (0.09)	1.47^{d} (0.22)	2.08^{d} (0.13)	3.04^{e} (0.23)	4.48^{f} (0.30)	1.40^{a} (0.74)	3.02^{bc} (1.01)	3.92^{c} (1.28)	4.81^{c} (1.46)	5.26^{b} (1.48)
LGF5	0.47^{b} (0.15)	1.00^{c} (0.14)	1.18^{b} (0.10)	1.83^{b} (0.17)	2.69^{cd} (0.10)	1.30^{a} (0.31)	1.96^{abc} (0.74)	2.24^{ab} (0.35)	2.74^{ab} (0.43)	3.31^{ab} (0.50)
LGF10	0.43^{b} (0.04)	0.92^{bc} (0.10)	1.15^{b} (0.13)	1.68^{b} (0.08)	2.72^{cd} (0.12)	1.57^{a} (0.39)	2.83^{bc} (0.51)	3.12^{bc} (0.45)	3.62^{bc} (0.33)	4.06^{b} (0.56)
CF5	0.34^{ab} (0.05)	0.71^{ab} (0.17)	1.15^{b} (0.07)	1.72^{b} (0.09)	2.83^{d} (0.22)	1.05^{a} (0.74)	3.13^{c} (0.62)	3.20^{bc} (0.77)	3.54^{bc} (0.44)	3.89^{b} (0.57)
CF10	0.37^{ab} (0.08)	0.90^{bc} (0.24)	1.50^{c} (0.21)	2.16^{c} (0.22)	3.41^{e} (0.34)	1.51^{a} (1.07)	2.86^{bc} (1.17)	3.50^{bc} (1.36)	4.07^{bc} (1.09)	4.81^{b} (1.29)
MIX5	0.24^{a} (0.05)	0.69^{ab} (0.11)	1.05^{b} (0.11)	1.66^{b} (0.20)	2.43^{bc} (0.16)	1.25^{a} (0.40)	1.76^{ab} (0.38)	2.87^{abc} (0.59)	2.87^{ab} (0.60)	3.53^{ab} (0.67)
MIX10	0.33^{ab} (0.13)	0.66^{ab} (0.14)	1.18^{b} (0.17)	1.61^{b} (0.13)	2.25^{b} (0.12)	1.47^{a} (0.86)	2.27^{abc} (0.83)	2.92^{abc} (1.20)	3.21^{abc} (0.93)	3.71^{ab} (0.81)

Note: Values in parentheses are standard deviations; letters indicate differences ($p < 0.05$) between groups depending on Duncan test.

There was no apparent relation between the fiber length and/or fiber type for WA and TS. It can only be stated that the hydrophilic nature of the fibers limited water absorption. Similarly, Araújo et al. [2006] found that the water absorption of GF-reinforced polyester composites decreased with an increasing fiber content. In contrast, the WA and TS values rose as the GF and CF ratios increased in the matrix in this study. Valente et al. [2011] also stated that poor adhesion was a reason for increased WA and TS values with an increasing reinforcement content. Moreover, reducing the polymer content negatively affected the WA and TS values as the high WF content with an increasing GF and CF ratio was also a reason for water interaction.

2. Mechanical properties

The synergic effect of chopped GF and CF on the mechanical properties of the WPC samples was investigated, as seen in Table 3. The reinforcement of the WPCs considerably improved the mechanical properties, which is necessary for usage areas requiring high mechanical properties such as construction, furniture, railways ties, etc. However, the different chemical structure causes inconsistency between wood and polymer [Chavooshi and Madhoushi 2013], which diminishes the mechanical properties, except MOE. A coupling agent was also used to reduce this inconsistency. It is considered that the anhydrite reacts with the -OH groups in the cell wall, and ester linkages occur (Rowell, 2012). Therefore, the bonding between polymer and wood fiber strengthens thanks to the coupling agent. The lowest FS was obtained from control samples. Nonetheless, there is significant improvement in the FS values with reinforcement. Compared to the control samples, the FS and MOE of the reinforced WPCs increased by 41% and 122%, respectively. Moreover, the highest FS was obtained by CF10. There is also considerable enhancement in the FS values thanks to the synergic effect of GF and CF. The combination of GF and CF provided almost the same improvement as CF10. On the other hand, when comparing

WPCs containing short and long GF, fiber length plays a crucial role in enhancing FS; nevertheless, it was still lower than the WPCs with CF. Moreover, it is stated that the WPCs reinforced with a mixture of fibers reached an FS value of almost nearly the strength of CF10.

Natural fibers have a high MOE and are essential in increasing the MOE of WPCs [Chaharmahali et al. 2008]. There was a rise of 47% in the MOE with the addition of WF to the polymer. Moreover, the reinforcement fiber also multiplied the MOE increase, reaching up to 122% compared to the control. Load transfer is vital in order to obtain high mechanical properties provided by the superior properties of GF and CF. Additionally, the growth in the mechanical properties with the long GF reinforcement is more significant than the short one, which might be incapable of transferring load, and also limits the increment in FS and MOE. However, CF10 was 25% higher than LGF10 for MOE. Thus, CF demonstrated its superiority compared to GF.

Table 3. Mechanical properties of reinforced WPCs

Groups	Flexural strength (MPa)	Modulus of elasticity (MPa)	Tensile Sstrength (MPa)
Neat-HDPE	47.75^{bc} (2.51)	2226^{a} (156)	17.85^{cd} (1.77)
Control	37.06^{a} (1.94)	3282^{b} (87)	13.73^{a} (1.43)
SGF5	38.05^{a} (3.74)	4289^{c} (110)	13.81^{a} (1.51)
SGF10	39.88^{a} (2.40)	4549^{d} (147)	16.92^{bc} (1.94)
LGF5	46.22^{b} (3.04)	4501^{d} (220)	19.09^{de} (1.05)
LGF10	47.90^{bc} (1.30)	5451^{f} (97)	19.84^{e} (2.42)
CF5	49.22^{cd} (2.71)	5278^{f} (131)	15.62^{b} (1.64)
CF10	51.97^{d} (1.74)	7279^{h} (416)	19.51^{de} (1.31)
MIX5	47.40^{bc} (2.63)	4810^{e} (113)	20.54^{e} (1.30)
MIX10	51.55^{d} (2.43)	5828^{g} (237)	20.81^{e} (1.30)

Note: Values in parentheses are standard deviations; letters indicate differences ($p < 0.05$) between groups depending on Duncan test.

Similarly, WF reduced the tensile strength of WPCs. In contrast, the reinforcement resulted in tensile strength increments, reaching up to 52%. The adhesion between the matrix and the reinforcement fibers is the main factor in obtaining a high tensile strength and FS. The highest tensile strength was obtained by MIX10, while the lowest was attained by the control samples. The synergic effect is more evident for tensile strength. The fiber length is also more critical for tensile strength. The WPC with long GF has nearly the same tensile strength as the WPC containing CF. Therefore, the mixture of fibers made a significant contribution to the tensile strength. Combining GF and CF improved the mechanical properties of the WPCs. In addition, the synergic effect reduced the cost of reinforced WPCs due to the lower amount of CF in the matrix.

3. Microscopic examination

The highest mechanical properties are associated with strong bonding between the reinforcement and the matrix, as well as homogeneous dispersion. The adhesion and distribution of GF and CF in the matrix were investigated by means of SEM after the tensile strength test. As seen in Fig. 1, the outstanding points are the gaps (white circles) and fiber paths (white arrows) on the cross-section of the WPCs. During the tensile test, the specimen is pulled in opposite directions, which forces the matrix to split into two parts. Therefore, the adhesion strength between the fiber and matrix is vital. As can be seen, most of the fibers were pulled out during the test, resulting in failure of the specimens. On the other hand, the long GF are different than the others as the fiber length is longer, and the resistance against pulling out increases, resulting in high mechanical properties of the WPCs containing these fibers.

Unterweger et al. [2015] stated that the inert surface and low surface energy of carbon fibers result in low adhesion between the polymer and CF, limiting the improvement in the mechanical properties. Nonetheless, when GF and CF were compared, the adhesion strength of the carbon fibers was more robust, resulting in fewer gaps and higher mechanical properties. Furthermore, the synergistic effect came to the fore and increased the mechanical properties. Khan et al. [2021] also stated that the wettability and high stiffness structure of carbon fibers affect strong bonding between the fibers and the matrix. The SEM micrographs reveal that the surface of CF is rougher than GF, which plays a crucial role in higher adhesion. After pulling, the polymer remnants on the CF surface exhibited higher resistance, which is the reason for the higher FS and tensile strength. Moreover, the distribution of fibers in the matrix is essential to transfer the load in the structure. Guan et al. [2021] stated that an increased CF content resulted in uneven distribution. On the other hand, homogeneous fiber distribution contributed to improvement in the mechanical properties due to the low content of fibers in this study (Fig. 1).

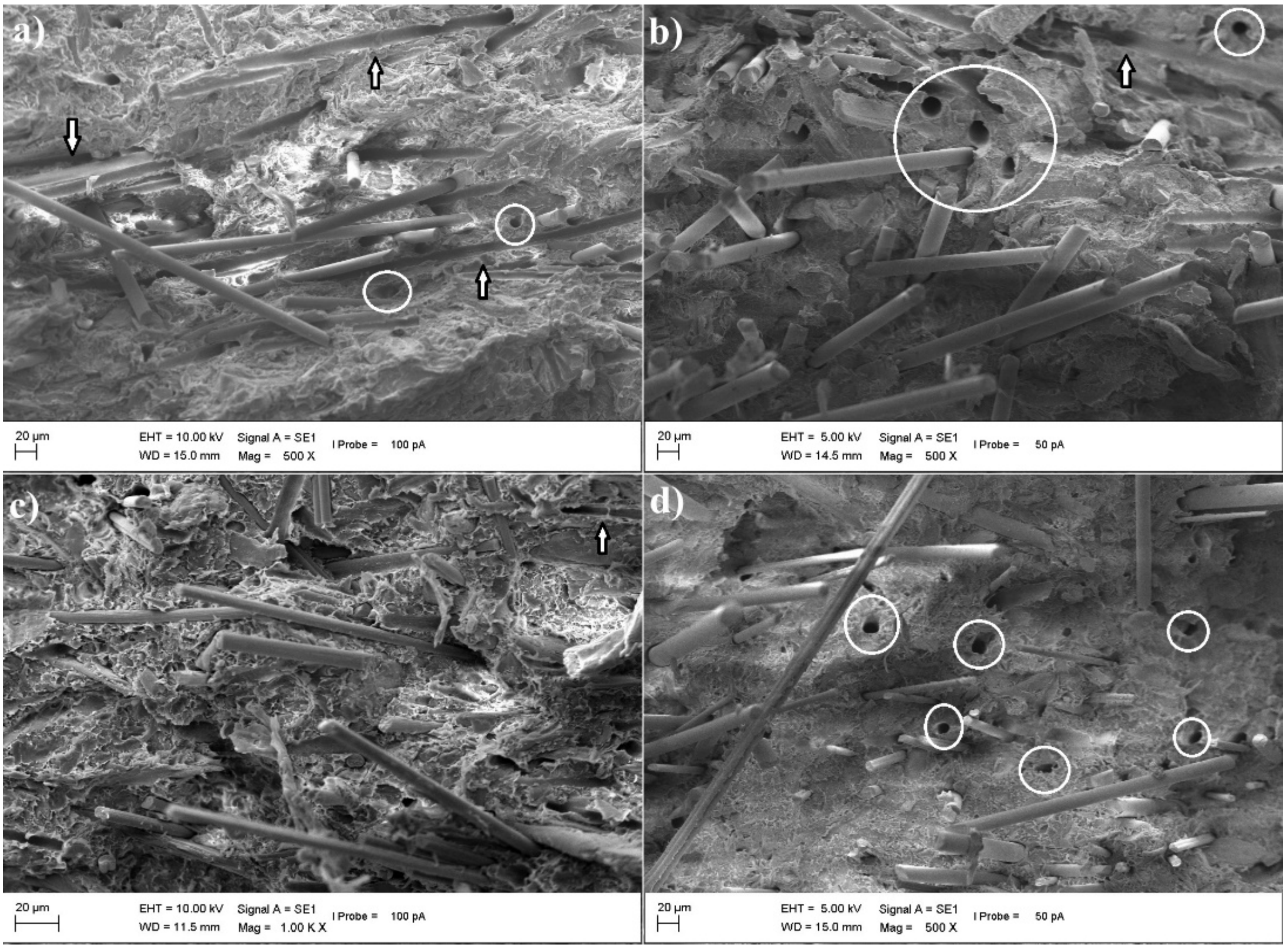

Fig. 1. SEM micrographs of reinforced WPCs; a) 10% SGF, b) 10% LGF, c) 10% CF, d) 10% MIX

4. LOI test

The synergic effect of GF and CF on the fire resistance performance was investigated with the LOI test, as seen in Fig. 2. The carbonization of the wood surface during burning increases the resistance against fire [Kozłowski and Władyka-Przybylak 2008]. On the contrary, as a petroleum-based material, the plastic quickly flamed, so it has low fire resistance. The LOI test showed an improvement in the fire performance of WPCs . WF only improved the fire resistance by up to 25% compared to neat-HDPE. Glass fiber and carbon fiber have higher degradation temperatures, which support fire resistance. Moreover, fire-resistant materials such as GF and CF create a barrier effect, retarding thermal degradation [Kocaman et al. 2022]. Budai et al. [2012] stated that GF reinforcement decelerated thermal oxidative decomposition. Nevertheless, adding these materials to the matrix causes a wick effect, decreasing the polymer's fire resistance, although the reinforcement fibers are recognized as materials having high fire resistance [Xue et al. 2020]. Hence, the improvement in fire resistance was limited after adding GF and CF to the matrix. In addition, an increase in the reinforcement fiber content raised the LOI values.

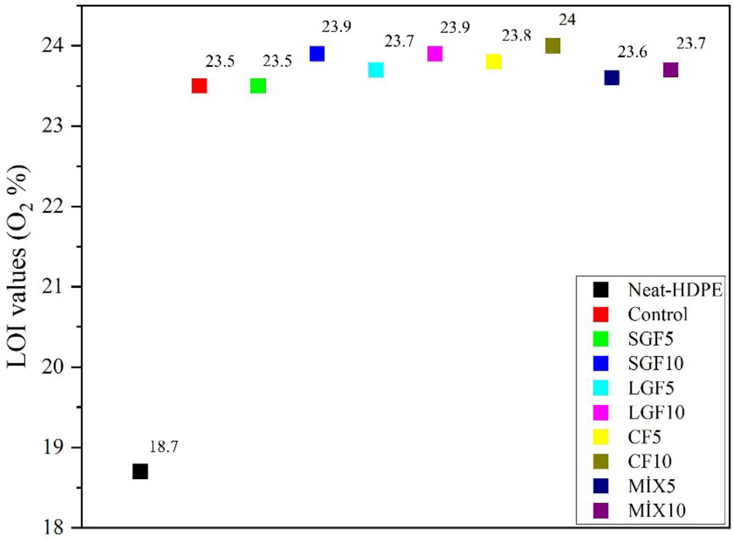

Fig. 2. LOI values of WPCs

Conclusions

GF and CF, as widely used reinforcement fibers, are each well-known to have excellent properties. In this study, the synergic effect of the fiber length, fiber ratio, and fiber type on the reinforcement of WPCs was investigated by means of studies of the physical, mechanical, fire resistance performance, and structural properties. The interaction of WPCs with water was restricted by reinforcement with GF and CF. Although the hydroxyl groups in the wood fibers interact with water molecules, the hydrophobic nature of the reinforcement fibers acted as a water barrier, reducing the WA and TS values compared to the control. Moreover, the mechanical properties also improved owing to the reinforcement. Reinforcement with GF and CF significantly increased the MOE of the WPCs up to 122% with the high elastic behavior of the added fibers. Moreover, the long GF made a substantial contribution to the tensile strength. In addition, the polymer remnants on the surface of CFs after the tensile strength test indicated high adhesion, resulting in higher resistance. The SEM observations also revealed that the opposing forces during the tensile test resulted in pulling-out of the fibers, which restricts the load transfer. However, the relatively long GFs made the pulling-out of fibers difficult, which is crucial in obtaining high strength. The effect of GF and CF on the fire resistance performance was definite although they degraded at high temperatures. They act as heat shields and distribute heat in the matrix. Nevertheless, they only retarded the fire; thermal degradation eventually occurred. Consequently, the superiority of the fibers merged with the WPCs, which resulted in higher physical, mechanical, and fire resistance performance.

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