Carbon Fiber Thermoplastic Compounds for the Automotive Industry: Structure-Property Relationship

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1. Abstract

Chopped carbon fiber (CF) based thermoplastic resin compounds play a crucial role in advancing the automotive industry by enabling significant weight reduction in vehicle components without compromising strength or durability. Their compatibility with existing manufacturing capacity in the ground of high-speed injection molding processes makes them ideal for mass production, reducing cycle times and manufacturing costs while maintaining design flexibility and structural performance.

Surface properties of CF play a critical role in determining the mechanical performance of carbon fiber reinforced thermoplastic composite as it enhances load transfer through the fiber-matrix interface. The compatibility between sizing materials and thermoplastic resins such as polypropylene (PP), and polybutylene terephthalate (PBT) is not just one solution as the resin chemistries are significantly different. Different sizing chemistries and applied contents have to be tailored to enhance adhesion with specific resin types due to their varying polarities and surface energies. In this work, different types of chopped carbon fibers with different sizing chemistries were compounded with SABIC PP and PBT materials and the impact of sizing chemistry, fiber shape and carbon fiber content on the mechanical performance of these compounds are evaluated.

2. Introduction

During the last decade, carbon fiber reinforced plastic (CFRP) has been embraced by many industries in their cutting-edge technologies. CFRP has been proven as a potential substitute of metals to design eco-friendly structures and to reduce CO2 emissions by light weighting of mass transport vehicles [1,2]. Mechanical properties of the composite materials rely on strong fiber matrix adhesion whereas, the sizing applied onto carbon fiber (CF) surface act as adhesion promoter supporting high adhesion of carbon fibers to the polymeric matrix. Accordingly, commercial carbon fibers are typically surface modified with a very thin layer of polymeric sizing for a targeted matrix. Sizing not only protects the fiber surface against damage during handling and textile processing but also ensures good wetting of the sized carbon fibers by the liquid resin during production of CFRP and thereby helps in transferring the stress to the CF [3-7].

Therefore, sizing is always applied onto the carbon fiber surface during the commercial production of CF. The sizing dispersions interact strongly with both the carbon fiber surface functional groups and the functional groups available in the matrix further enhances the bonding between the components [11]. Typically, polymeric sizing of chemical functionalities like the target polymer matrix are used to achieve maximum compatibility. Moreover, sized carbon fibers exhibit significantly high surface energy that help in good wetting of the fibers with the liquid composite resin [4,5]. Establishment of a structure-property correlations has always been an important subject in the field of material science. An understanding of correlations between the structure of fiber sizing and the mechanical parameters of CFRP will further guide to improve the fiber matrix interaction. Accordingly, a systematic investigation of fiber-matrix interaction and identification of the influencing parameters are highly required.

In this paper, chemical and structural information of five different types of chopped carbon fibers were used as reinforcing fiber in the composites. Mechanical properties of corresponding composites with PP and PBT materials have been described. An attempt has been made to establish a correlation between the chemical functionality type and content of the applied sizing and the structure of CF, and their corresponding composite mechanical properties.

3. Experimental Procedure

3.1. Materials

Six different types of chopped carbon fibers available commercially were received from various suppliers. Details of these CF samples as available from their corresponding technical data sheet are provided in Table 1. Polypropylene (SABIC® PP 595A from) and polybutylene terephthalate (PBT, VALOXTM 215HPR from SABIC) were used as resin matrix (Table 2).

Table 1. Details of chopped carbon fiber properties as available from technical data sheets

Supplier	Code	Tensile Strength (MPa)	Tensile Modulus (GPa)	Sizing Type	Sizing Level (wt%)	Preferable Matrix
1	CF1-S1	4,200	240	PU	1.5 to 2.0	ABS, LCP, PA, PC, PBT, PET, POM, PPO
	CF1-S2	4,200	240	PA	1.5 to 2.0	PA and PBT
2	CF2-S3	4,137	242	-	1.5	PE and PP
3	CF3-S4	4,000	240	Ep	2.8	Epoxy, polyester
4	CF4-S5	4,100	240	PU/ Ep	3.8/ 0.2	ABS, PC, PBT, PA

Table 2. Material properties of thermoplastic resin

Grade Name	Flexural Modulus (MPa)	Tensile Strength at yield (MPa)	Engineering Tensile Strain at break (%)	Density (kg/m^3)
SABIC® PP 595A	1800	35	11	905
Valox™ 215HPR	2340	51	10	1310

3.2. Formulation

In the present work, composites reinforced with short carbon fibers (SCF) were prepared by extrusion compounding and samples prepared for testing using injection molding technique. The compositions of all the specimens are listed in Table 3 for PP and PBT resins.

Table 3: Material composition for the CF/PP and CF/PBT compound

CF Grade	PP					PBT			
	CF Weight Fraction (wt%)								
	6	10	16	25	40	10	20	30	40
CF1-S1	√	√	√	√	√			√	
CF1-S2				√		√	√	√	√
CF2-S3				√				√	
CF3-S4				√				√	
CF4-S5				√				√	

The composite compounds were prepared by feeding the chopped carbon fiber into the polymer melt using a co-rotating twin screw extruder. The heating zones were set between 210 – 230oC. The compounded extrudates were immediately quenched in water and cooled in air till ambient temperature. Then the extruded strands were chopped into granules and dried.

3.3. Processing and Testing

All the standard specimens were prepared by using a twin-screw injection molding machine maintaining the barrel temperature of 210–230°C. The dimensions of all these specimens were according to the ISO standard as shown in Figure 1. Tensile specimens were prepared as per ISO 527 standard [12]. Tensile properties were measured using the instrument Zwick Z020 at room temperature (23oC) at a speed of 5 mm/ min. Engineering stress and strain were recorded using the load cell and crosshead displacement and original cross-sectional area respectively. Charpy notched impact was measured by following ISO 179/1eA method [13]. Impact specimens were loaded in the instrument Zwick HIT25P-2 at room temperature (23oC) using a hammer of 1.0 J. Flexural stress-strain was evaluated by following ISO 178 method [14]. Flexural properties were measured using Zwick Z010-2 at room temperature (23oC) at a speed of 2 mm/min.

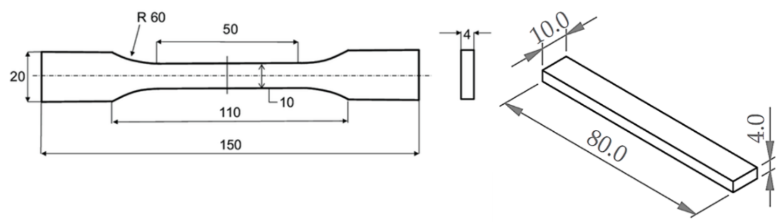

Figure 1: Dimension of Tensile and Flexural samples

All chopped carbon fiber samples used in this study were studied under microscope to understand the cross-sectional geometry of the individual fiber. CF samples were sputter-coated with gold as per the standard process for sample preparation. Gold coated samples were then observed in a ZEISS make (model EVO-14) scanning electron microscope.

4. Results

4.1. Effect of CF Content

As a first step, to determine the maximum possible loading of CF to achieve the best combination of mechanical properties, composites with variable loading of CF were evaluated. In case of PP resin, the levels of CF loading were used 6, 10, 16, 25 and 40 wt% of 'CF1-S1'.

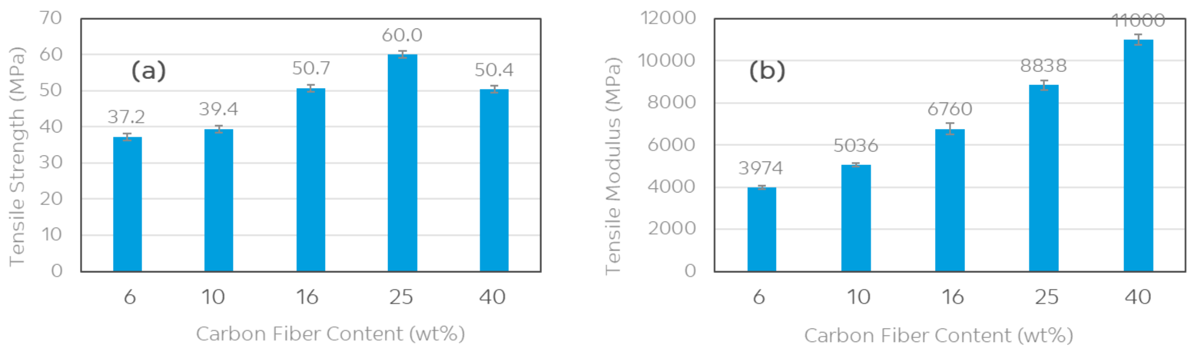

Figure 2: (a) Tensile strength (b) tensile modulus for PP reinforced with chopped carbon fiber

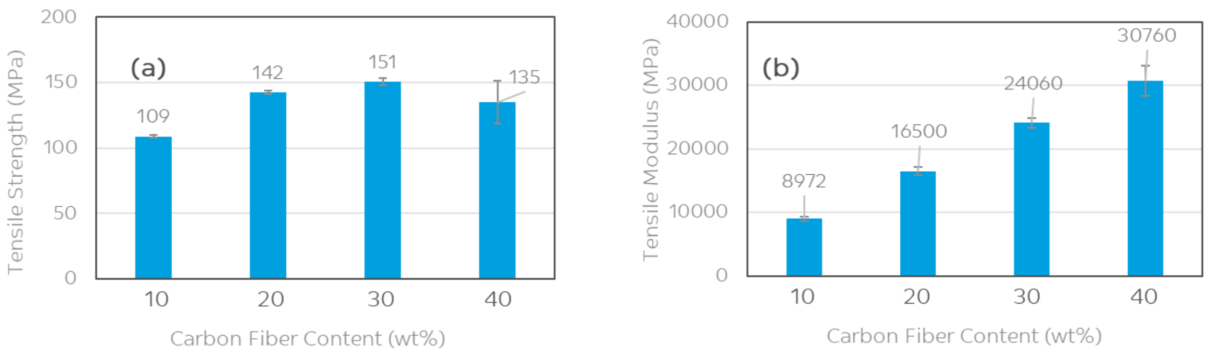

Figure 3: (a) Tensile strength (b) tensile modulus for PBT reinforced with chopped carbon fiber'

As shown in Figure 2 and Figure 3, it was observed that tensile strength increased with increasing CF loading for both PP and PBT resins. The highest CF loading of 25 wt% was used for PP resin whereas for PBT resin a loading of 30 wt% showed the highest tensile strength among the series. After the threshold loading of CF, further increase in CF loading led to decrease in composite strength. This is possibly due to the decrease in fiber length upon increasing the CF content. It is well known that with increase in CF loading, CF length tends to decrease because of the friction between fibers, and equipment surface etc.

4.2. Effect of CF Sizing

CF/PP Compound

Tensile properties of five types of PP-CF composites with different types of CF sizing has been shown in Figure 4. It is apparent from this evaluation that the composite reinforced with ' CF2-S3' showed the highest tensile strength and modulus values. 'CF2-S3' is the only grade available with sizing targeted for PE and PP resin among all these five different grades. The mechanical properties measured were also corroborated with the fact that the sizing might be the most appropriate. This clearly demonstrates that a sizing with similar chemical functionality enhances the fiber surface and resin interaction which, in turn, results into improved mechanical properties. Epoxy sized 'CF3-S4' showed tensile strength at break value next to 'CF2-S3'. This possibly indicates that the epoxy sizing applied on the CF may contain significant amount of aliphatic content that helped to establish a good fiber-polymer interaction.

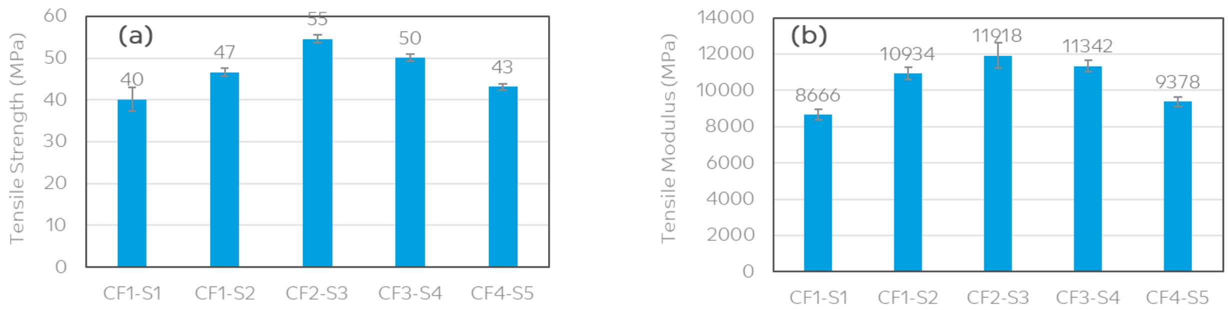

Figure 4. (a) Tensile strength (b) tensile modulus for PP reinforced with different types of CFs

Flexural properties of the PP-CF composites is shown below in Figure 5. Similar to tensile properties, all these PP-CF composites showed similar trends of performance in terms of flexural properties. 'CF2-S3' with the best suitable sizing for polyolefin demonstrated the highest flexural strength among all these CF grades.

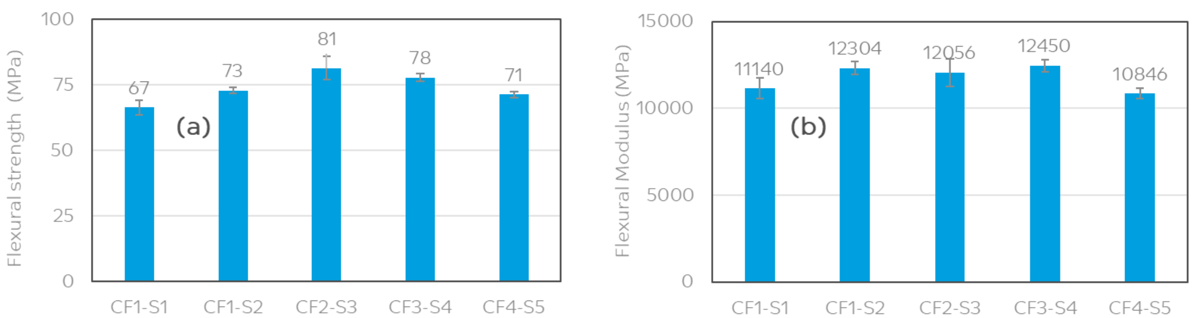

Figure 5. (a) Flexural strength (b) flexural modulus for PBT reinforced with different CF grades

Impact strength of PP-CF composites is shown in Figure 6. It is apparent from the impact strength values that all the PP-CF composite samples in the series showed impact strength in the range of 3.6 KJ/m2 to 4.1 KJ/m2. It is interesting to observe that statistically the impact strength value of 'CF1-S1', 'CF1-S2' and 'CF2-S3' are similar in terms of impact performance whereas 'CF3-S4' and 'CF4-S5' based PP-CF composite samples showed around 15% higher impact strength compared to other fibers.

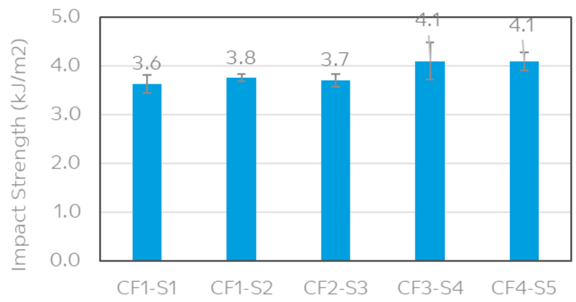

Figure 6. Impact properties for PP reinforced with different CF grades (with 25 wt%)

CF/PBT Compound

Tensile properties of PBT-CF composites is shown in Figure 7. In case of PBT resin, it is clear from Figure 7(a) that three PBT-CF composites with 'CF1-S2', 'CF3-S4' and 'CF4-S5' demonstrated relatively improved tensile strength compared to other two composites reinforced with CF grades. Similar trend was also apparent for tensile modulus property for all these PBT-CF composites. This observation clearly corroborates with the chemical functionalities available in the sizing type of the respective CF (ca. Table 1) which also makes the basis for the guideline toward preferable matrix. It is interesting to note that CF sized with polyamide ('CF1-S2') and epoxy ('CF3-S4') showed similar efficiency in terms of resin-fiber interaction resulting in similar tensile strength and tensile modulus. This indicates that both polyamide as well as epoxy can perform similarly for PBT resin if the molecular structures of these sizing are designed appropriately. However, a combination of polyurethane and vinyl ester (CF4-S5) in the sizing resulted in the highest level of resin-fiber adhesion leading to the highest tensile strength and tensile modulus among the series. This can possibly be explained by the molecular interaction between terminal hydroxy functionalities in PBT with epoxy and terminal isocyanate functionality present in 'CF3-S4' and 'CF4-S5', respectively.

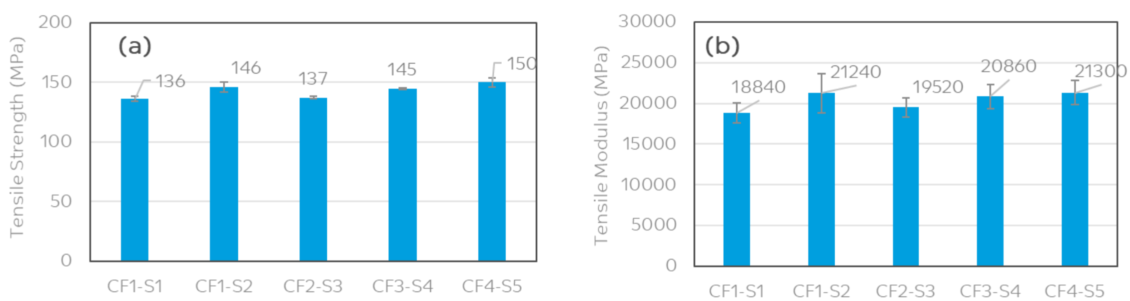

Figure 7: (a) Tensile strength (b) tensile modulus for PBT reinforced with different types of CFs

Flexural properties of PBT-CF composites is shown in Figure 8. Significant difference in flexural strength among the series can be observed for different PBT-CF composites with different types of sizing. Therefore, selection of right CF in terms of appropriate sizing plays a crucial role while developing a composite material. CF with the appropriate sizing (combination of epoxy and polyurethane in 'CF4-S5') demonstrated the highest flexural strength and flexural modulus values.

CF ('CF2-S3') most probably sized with polyolefin-based sizing showed poor flexural properties because of the incompatible sizing.

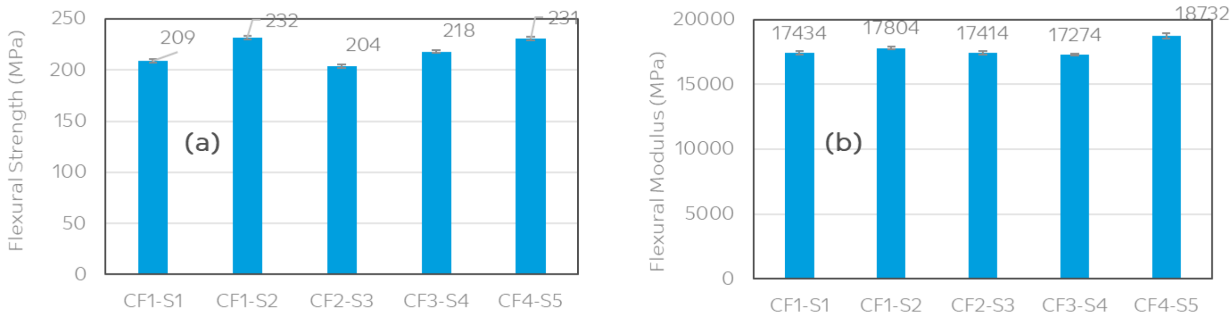

Figure 8. (a) Flexural strength (b) flexural modulus for PBT reinforced with different CF grades

Impact strength values for all the PBT-CF composite samples is shown in Figure 9. Compared to the PP-CF composites, PBT-CF composites showed higher impact strength in the range of 5.2 KJ/m2 to 6.5 KJ/m2. Among all these different types of CFs' used for PBT-CF composites, 'CF3-S4' and 'CF4-S5' demonstrated improved impact strength. 'CF3-S4' is sized with epoxy sizing and 'CF4-S5' is sized with a combination of polyurethane and epoxy. Both these 'CF3-S4' and 'CF4-S5' are appropriately sized with the required chemical functionalities for better surface adhesion with PBT resin matrix.

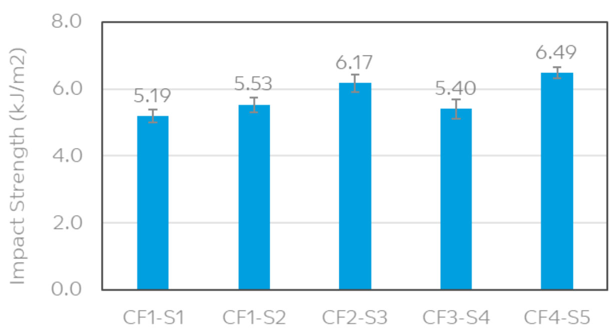

Figure 9: Impact properties of PBT-CF composites reinforced with different CF grades (with 30 wt%)

4.3. Effect of Fiber Shape

Cross sectional shape and diameter were measured using Scanning Electron Micriscopy. Details have been tabulated in Table 5. Images of cross-section of all these carbon fibers is shown Figure 10.

Table 5. Cross sectional shape and diameter of the carbon fibers

CF Grade	Cross section shape	Cross section diameter
CF1-S1	Kidney bean shaped	8 to 10 µm
CF1-S2	Kidney bean shaped	8 to 10 µm
CF2-S3	Kidney bean shaped	8 to 9 µm
CF3-S4	Kidney bean shaped	8 to 9 µm
CF4-S5	Circular	6 to 7 µm

It is quite interesting to observe that both the composite samples (PP-CF and PBT-CF) based on 'CF4-S5' demonstrated higher impact strength among the series. It can be seen from Table 5 that this CF is the only one with circular shape and smallest diameter (this leads to higher surface area). Moreover, the sizing applied onto the CF surface is based on a mixture of epoxy and polyurethane. Considering this excellent combination of characteristics, CF4-S5 may be the most interesting fiber among the series in terms of efficient stress transfer from resin to CF. This, in turn, resulted in better dispersion of impact energy during impact strength measurement.

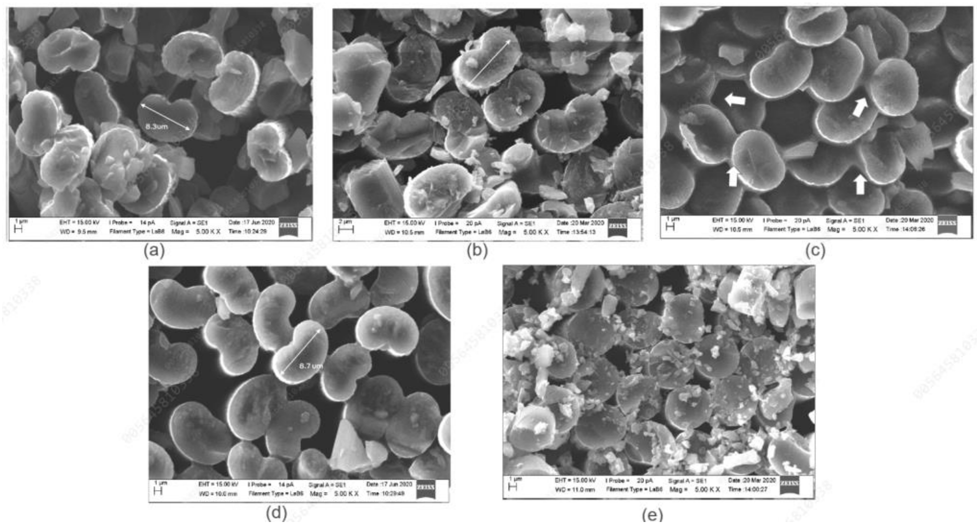

Figure 10. Carbon fiber cross sectional shape- CF1-S1 (a), CF1-S2 (b), CF2-S3 (c), CF3-S4 (d), CF4-S5 (e)

5. Discussion

An attempt has been made to establish a relationship between structure of the CF sizing and final mechanical properties. Available chemical functionalities in the sizing of different CFs' were gathered as provided by the suppliers. Scanning electron microscope (SEM) image analyses showed the cross-sectional shape and ferret diameter of the carbon fibers from different suppliers. Various mechanical properties of the standard specimen prepared after injection molding of composite samples based on five different types of chopped CFs' and, PP and PBT as resin matrix. Chemical and structural information as deduced from the de-formulation analysis revealed a good correlation between the molecular structure of the film former used in the CF and the mechanical properties of their corresponding composites.

In Figure 11, two critical mechanical properties, i.e., tensile and impact strength of both the PP and PBT based composites are shown. It is apparent from these graphs that differently sized CF (with different types of chemical functionalities as well as cross-sectional shape and diameter) plays differently with the target resin matrix. Chemical functionalities in the sizing establish a chemical interaction via the polymer backbone as well as terminal functionalities whereas the cross-sectional diameter and shape determine the efficiency of CF surface to resin adhesion. This is very helpful for efficient transfer of load from the resin to fiber level. Therefore, in conclusion, selection of CF with appropriate sizing is crucial to achieve the maximum level of mechanical properties.

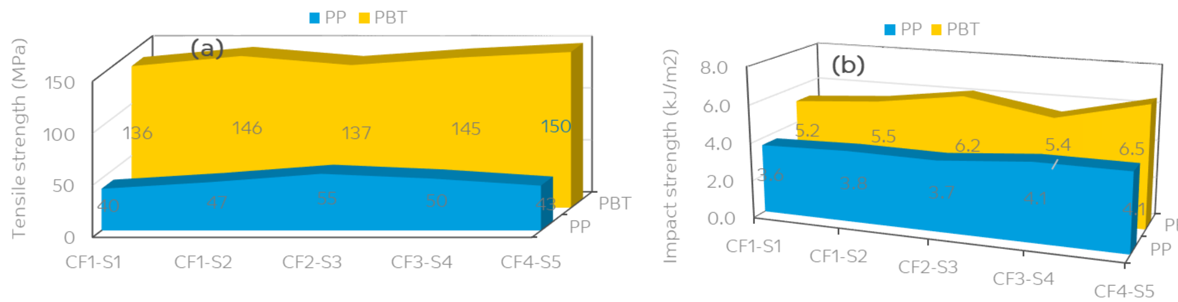

Figure 11. Tensile strength (a) and Impact strength (b) of PP and PBT based composites using differently sized chopped CFs'

6. References

[1] C. Soutis, "Fibre reinforced composites in aircraft construction," Prog. Aerosp. Sci. 41, 2 (2005): p. 143-151, doi.https://doi.org/10.1016/j.paerosci.2005.02.004.

[2] P.K. Mallick, Fiber-reinforced Composites: Materials, Manufacturing, and Design, 3rd ed. (Boca Raton, Florida: CRC Press, 2007), p. 638, doi. https://doi.org/10.1201/9781420005981.

[3] M. Sharma, S. Gao, E. Mäder, H. Sharma, L.Y. Wei, J. Bijwe, "Carbon fiber surfaces and composite interphases," Compos. Sci. Technol. 102, 3 (2014): p. 35–50, doi.10.1016/j.compscitech.2014.07.005.

[4] A. Kafi, M. Huson, C. Creighton, J. Khoo, L. Mazzola, T. Gengenbach, F. Jones, B. Fox, "Effect of surface functionality of PAN-based carbon fibres on the mechanical performance of carbon/epoxy composites," Compos. Sci. Technol. 94 (2014): p. 89–95, doi.10.1016/j.compscitech.2014.01.011.

[5] Q. Ma, Y. Gu, M. Li, S. Wang, Z. Zhang, "Effects of surface treating methods of high-strength carbon fibers on interfacial properties of epoxy resin matrix composite," Appl. Surf. Sci., 379 (2016): p. 199–205, doi. https://doi.org/10.1016/j.apsusc.2016.04.075.

[6] B. Fernández, A. Arbelaiz, A. Valea, F. Mujika, I. Mondragon, "A comparative study of the influence of epoxy sizings on the mechanical performance of woven carbon fiber-epoxy composites," Polym. Composite, 25, 3 (2004): p. 319–330, doi. https://doi.org/10.1002/pc.20026.

[7] X. Yuan, B. Zhu, X. Ca, J. Liu, K. Qiao, Y. Junwei, "Optimization of interfacial properties of carbon fiber/epoxy composites via a modified polyacrylate emulsion sizing," Appl. Surf. Sci., 401 (2017): p. 414–423. doi. 10.1016/j.apsusc.2016.12.234.

[8] J. Liu, Y. Tian, Y. Chen, J. Liang, "Interfacial and mechanical properties of carbon fibers modified by electrochemical oxidation in (NH4HCO3)/(NH4)2C2O4.H2O aqueous compound solution," Appl. Surf. Sci., 256 (2010): p. 6199–6204, doi. 10.1016/j.apsusc.2010.03.141.

[9] P. Morgan, Carbon fibers and their composites, 1st ed. (Boca Raton, Florida: CRC Press, 2005), p. 1200, doi. https://doi.org/10.1201/9781420028744.

[10] Z. Li, S. Wu, Z. Zhao, L. Xu, "Influence of surface properties on the interfacial adhesion in carbon fiber/epoxy composites," Surf. Interface Anal., 46, 1 (2014): p. 16–23, doi. https://doi.org/10.1002/sia.5340.

[11] X. Yuan, B. Zhu, X. Ca, J. Liu, K. Qiao, Y. Junwei, "Optimization of interfacial properties of carbon fiber/epoxy composites via a modified polyacrylate emulsion sizing," Appl. Surf. Sci., 401 (2017): p. 414–423, doi. 10.1016/j.apsusc.2016.12.234.

[12] ISO 527-1:2019, "Plastics — Determination of tensile properties" (Geneva, Switzerland: ISO).
[13] ISO 179-1:2023, "Plastics — Determination of Charpy impact properties" (Geneva, Switzerland: ISO).
[14] ISO 178:2019, " Plastics — Determination of flexural properties" (Geneva, Switzerland: ISO).