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ORIGINAL RESEARCH

Mechanical and high velocity impact performance of a hybrid long carbon/glass fiber/polypropylene thermoplastic composite

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Abstract

This research explores mechanical and high velocity impact response of hybrid long carbon/glass fiber-reinforced polypropylene thermoplastic composites (HLFT) with different fiber lengths. The work examines three hybrid long fiber thermoplastic composites, i.e., 5, 10 and 20 mm. The HLFTs were prepared by a combination of extrusion and pultrusion processes and using a cross-head die. Tensile and Izod impact tests were carried out to evaluate the mechanical performance of each HLFT compound. A gas gun with a spherical projectile was used to conduct high velocity impact tests at three velocities of 144, 205 and 240 m/s. The results showed that internal mixing operation caused extensive reduction in fiber length of all three LFT lengths. Tensile strength, modulus and Izod impact test results were the indications of higher values with increase in HLFT length. Comparison of these results for the HLFT with that of corresponding glass/PP LFTs, adopted from earlier work by Shayan Asenjan et al. (J Compos Mater 53:353–360, 2019), showed better performance of HLFT. The high velocity impact results showed a steady higher impact performance with the increase in HFLT fiber length for all impact velocities tested. Comparison of HLFT high velocity impact performance revealed better results for all impact velocities tested with that of the corresponding glass/PP LFT composite.

Keywords Long fiber thermoplastic composite · High velocity impact · Hybrid carbon/glass fiber · Mechanical properties

Introduction

Utilization of thermoplastic composites in various industries, such as aerospace, military and automotive, has increased significantly due to their good performance and recyclability characteristic. Composite with thermoplastic matrix can be divided into two groups of long fiber (LF) and short fiber (SF) composites. Long glass fiber (LGF)-reinforced thermoplastic composites are a new class of polymeric materials that have a special place in composite materials. This is because of their properties which are strongly influenced by the fiber final length in composite specimens. LGF-reinforced thermoplastic composites are usually prepared by a combination of pultrusion and extrusion processes. In these two processes, continuous glass fibers with a polymer matrix surrounding them are pulled through a cross-head die. LGF-reinforced thermoplastic composites compared to SGF exhibit excellent mechanical property, in particular, impact performance. The long length of the fibers leads to improved mechanical properties of the composite specimens, however, it also leads to an increase in the polymer melt viscosity. Therefore, the long glass fiber thermoplastic composites endure higher shear force, leading to sever fiber length shortening [1]. Polypropylene (PP) as the most common matrix used in LGF is a semi crystalline thermoplastic polymer which has good processing features, high chemical stability and electrical insulation. However, it has low mechanical properties which limit its usage [2]. Literature review revealed quite a few reports on the long glass fiber thermoplastic composites usage. Weidenmann et al. [3] reported the temperature and time dependency of long glass fiber-reinforced polypropylene. They reported that the increase in strain rate results in an increase of the elastic modulus with decreasing service temperature. Thomason et al. [4–6] in a series of reports investigated the mechanical performance of injection moulded long glass fibre-reinforced polypropylene with a glass fibre content in the range

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of 0–73 wt%. According their result, composite strength and impact resistance exhibited a maximum in performance in the 40–50 wt% reinforcement content. He et al. [7] studied the mechanical properties of long glass fiber-reinforced polypropylene composites and their influencing factors. They reported the improvement of impregnation quality and thereby mechanical properties of LFT with control of the MFI value of polypropylene, impregnation time, melt temperature, and addition of compatibilizer. Fu et al. [8] compared the tensile properties of short glass and short carbon fiber-reinforced polypropylene composites. Their studies showed that by increasing the percentage of the fiber, the mean final length of the fibers will be reduced. They also claimed that the composite strength is more dependent on the mean final fiber length than on the fiber percentage while the composite modulus is more dependent on the fiber percentage than on the mean final fiber length. Kada et al. [9] studied the effect of the carbon fiber volume fraction on the mechanical and thermal properties of short carbon fiber-reinforced polypropylene composites, and concluded that by increasing the fiber volume fraction the mechanical property and thermal stability of specimens increased. Zhang et al. [10] investigated the effect of the injection temperature on the mechanical properties of PP/LGF composites. Their finding showed that the mechanical properties in terms of the injection temperature have an optimal limit. The same author published work on the influence of fiber length and fiber dispersion on the mechanical properties of PBT/LGF composites [11]. He showed that optimal length of fiber leads to an increase in the mechanical properties, but after optimal length, the increase of the length leads to the loss of properties. Kumar et al. [12] studied the effect of fiber length, fiber content and compatibilizer content on the properties of PP/LGF composites. They optimized the amount of the compatibilizer and then focused on the length of fiber and fiber content. Their study indicated that with increasing the fiber content the mechanical properties, such as flexural properties and tensile properties increased. Literature review on the subject of hybrid reinforcement utilization in LFT composites revealed limited published studies in open literature. Uawongsuwan et al. [13] investigated hybrid twisted- and untwisted-jute yarn with glass fiber LFT. They reported better mechanical performance with longer fiber length. Lee et al. [14] reported electrical and mechanical performance of hybrid carbon/epoxy LFTs. They noted that hybridization affects strength more than modulus. Recently, Panthapulakkal et al. [15] focused on natural fiber and waste and recycled carbon fiber benefiting from a lightweight structure. Although an extensive research on the mechanical and physical properties of long fiber thermoplastic composite structures has been published, but, due to the lack of adequate studies on the behavior of thermoplastic composites under a high velocity impact, the decision was made to pursue the study in the current context. In our latest published work [16], the effect of glass fiber length on the high velocity impact performance of PP/LGF composites has been reported. The results showed that the increase in the initial length of the LFTs leads to an increase in the final fiber length in the compound, and consequently, higher mechanical properties and better high velocity impact resistance of composite samples. Hybridization is the natural next step in the study of material optimization. In this study, the effect of fiber length on the mechanical properties and, in particular, high-velocity impact behavior of hybrid composites i.e., long carbon and glass fiber-reinforced polypropylene (PP/LCF/LGF) has been investigated. The main impetus is to benefit from high stiffness and strength associated with carbon fiber as well as their insensitivity towards strain rate and also low cost of glass fiber all in one compound. The study will also investigate the strain rate effect of hybrid compound by conducting high-velocity impact tests in three different velocities.

Experimental

Materials

Polypropylene (PP, Z30S, Maroon Petrochemical, Iran) homopolymer with a melt flow rate of 18 g/10 min was used as the matrix in the compound. Maleic anhydride grafted polypropylene (PP-*g*-MA, Karabond, Iran) 29 wt% was used as coupling agent to improve the adhesion between the thermoplastic matrix and reinforcing fiber phase. Continuous E-glass fiber roving and continuous carbon fiber roving were also used as reinforcement phases. The characteristics of the reinforcing materials are reported in Table 1.

Preparation of hybrid long fiber thermoplastic/polypropylene (HLFT/PP)

For the preparation of hybrid thermoplastic granules, a combination of pultrusion and extrusion processes was used. To prepare a polymer melt for impregnating the reinforcing phase, a single-screw extruder with $L/D = 26$, $L = 52$ cm and three thermal zones was employed. The temperatures of the three thermal zones were 190, 220 and 235 °C, respectively.

Table 1 Characteristics of the reinforcing materials

	Tex	Diameter	Density (g/cm^3)	Company
E-glass fiber	2400	40 μm	2.4	CAM ELYAF, Turkey
Carbon fiber	12 K T300	7 μm	1.78	ARROWTEX, India

The screw speed was 15 rpm. A cross-head die with three rollers to help spread the fibers was used for the impregnation of the hybrid carbon/glass fiber with polypropylene matrix. In all tested samples, 35 wt% of carbon and glass fiber roving each was used. The impregnation temperature was 245 °C. Considering the fact that thermoplastic materials have high melt viscosity, 1 wt% dicumyl peroxide was used to reduce the melt viscosity and facilitate the polymer melting flow inside the extruder and improve the quality of impregnation. The composition of the polymer compound used in the extruder was 70% polypropylene, 29% PP-*g*-MA and 1% dicumyl peroxide. Diamond tip pelletizer was used to produce hybrid LFT (HLFT) in 5, 10 and 20 mm length (Fig. 1).

Preparation of samples

Due to the high fiber content in the hybrid LFT (approximately 70 wt%) and difficulty associated with processing the compound at such content of the fiber, it was decided to dilute the LFTs with virgin PP and reduce the fiber content to 20 wt%. To prepare the hybrid composite samples with a fiber mass fraction of 20 wt%, carbon/glass hybrid fiber was diluted with neat polypropylene granules to obtain a hybrid LFT with 20 wt% fiber content. An internal mixer (HAAKE W50, Germany) was used to achieve a homogeneous polymer composite compound. Compression molding (10 min at 240 °C) was used by a hydraulic hot press to prepare hybrid composite plates in size of 12 cm × 12 cm. Although extensive fiber shortening occurred during internal mixing, but the study of fiber length of hybrid compound before and after compression molding revealed no significant change.

Physical and mechanical tests

Burn off test was conducted per ISO 1172 to determine the fiber mass fraction in the granules of the hybrid composites. The result showed that HLFT was produced with 70 wt% of fiber reinforcements comprising of 35 wt% carbon and 35 wt% glass fiber roving. Due to the high fiber mass fraction in LFT compound and to make the compound processable, the compound was diluted with virgin PP by an internal mixer to obtain an overall fiber reinforcement of 20 wt% comprising of carbon and glass.

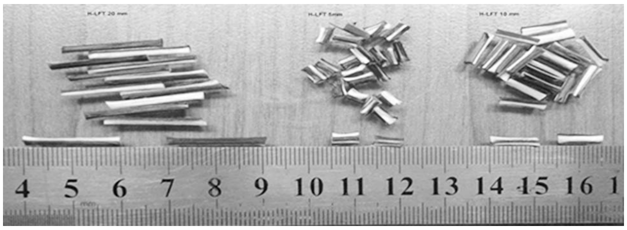

Fig. 1 Hybrid carbon/glass/PP long fiber thermoplastic composites with a fiber length of 5, 10, and 20 mm

Izod impact test

Izod notched impact properties were determined according to the procedures stated in ASTM D-256 using a 20 J capacity Zwick impact tester, Germany. The specimen size for the Izod impact test according to the mentioned standard was 64 × 12.7 × 3.2 mm. The data reported here are the average of five specimens tested.

Tensile test

The tensile tests on all composite specimens were carried out per ASTM D 638 Type IV by a universal testing machine (Santam, 150 kN, Iran) at 2 mm/min cross-head speed. The data reported here are the average of five specimens tested.

High velocity impact

High velocity impact performance of the specimens was investigated by a smooth bore gas gun using a stainless steel spherical projectile with a diameter of 8.7 mm and 2.71 g weight. The impact velocity test range was from 144 to 250 m/s. A chronograph (Shooting Chrony, Canada) was used to measure the impact and residual velocity (exit velocity) of the projectile. Energy absorption capacity of the HLFT composite was calculated using Eq. 1, which is based on the conservation of energy. The energy loss through heat, friction and noise is neglected

$$E = \frac{m}{2}V_i^2 - \frac{m}{2}V_\mathrm{r}^2 \tag{1}$$

where V_i, V_r and m are the initial velocity, residual velocity and projectile mass, respectively.

Results and discussion

Prior to mechanical and high velocity impact performance study, the hybrid LFT molding compound was checked for the fiber final length (after internal mixing operation). This was carried out by a light microscope (OLYMPUS\\ Philippines SZ61). It is worth mentioning that the internal mixing operation is vital for obtaining homogeneous molding compound. Analysis of the microscope images showed extensive fiber breakage after internal mixing operation for all three hybrid LFTs fiber lengths used. Table 2 depicts all three hybrid LFTs final fiber lengths after internal mixing operation. It shows that the final fiber length (after internal mixing operation) remains higher in each category, this is despite extensive reduction in HLFT original fiber length

Table 2 Hybrid LFT fiber length before and after internal mixing operation

Initial hybrid LFT fiber length (mm)	Average HLFT final fiber length after internal mixing (mm)	STD
5 mm	1.46	0.41
10 mm	1.94	0.40
20 mm	2.80	0.44

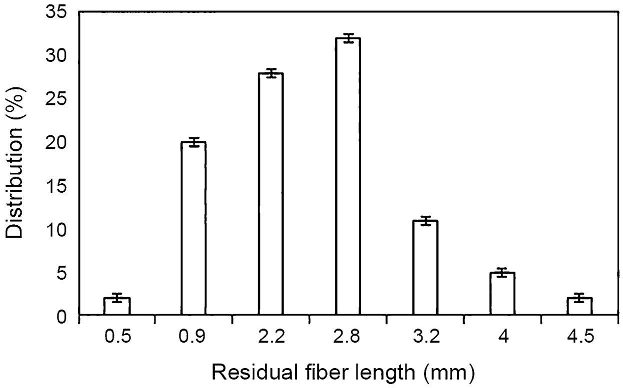

Fig. 2 Fiber length distribution after internal mixing for 20 mm original length HLFT

(i.e., 5, 10 and 20 mm initial HLFT fiber length). Other factor which needs to be considered in this regard is the distribution of both fiber lengths after internal mixing. This has been depicted in Fig. 2. The figure shows some distribution charts for the HLFT fibers length in the compound with the initial fiber length of 20 mm. This figure represents that the highest percentage of the residual fiber length is 2.8 mm for the initial hybrid fiber length of 20 mm. The distribution also shows that the fiber length above 3 mm is less than 10%. Similar results have been reported for the long glass fiber-reinforced thermoplastic composites based on poly (butylene terephthalate) [10].

Tensile and izod impact performance of the hybrid carbon/glass/PP LFT compounds were investigated and compared with that of glass/PP LFT compound (Table 3). The latter results were adopted from the author's pervious published work [16]. The results of the tensile strength and modulus for the hybrid LFT are presented in Table 3. The results show the increase in tensile strength and modulus with the increase in hybrid LFT length. These results show 10.2% and 20% increase in the strength as HLFT length increases from 5 to 10 mm and then from 10 to.

20 mm, respectively. The similar assessment made for the tensile modulus revealed 6.6 and 16.3% increase with the increase in HLFT length from 5 to 10 mm and then to 20 mm, respectively. This, as expected, indicates strong dependence of both strength and stiffness of the HLFTs to the fiber final length. Comparing the tensile strength of the glass/PP LFTs [16] and that of corresponding HLFT for the three LFT lengths (5, 10 and 20 mm) shows 29.5, 35.6 and 50.6% increase in the tensile strength for the HLFT composites, respectively. Similarly, tensile modulus comparison for the two LFTs shows, respectively, 39.2, 37.4 and 52.5% increase in the HLFT for the 5,10 and 20 mm original fiber length. This better performance in strength and stiffness may directly be attributed to the presence of higher strength and stiffness carbon fiber in the compound. Considering the above comparison and also comparing the two fiber densities (Table 1), one can immediately see the benefit of hybridization. The Izod impact results depicted in Table 3 revealed an increase of 11.5% and 5.2% in impact strength as HLFT original length increased from 5 to 10 mm and then to 20 mm, respectively. It may be noted that although the increase in impact strength was expected with increase in HLFTs fiber length, the decrease in this rate when the HLFTs length increases from 10 to 20 mm signifies a fact that there is a limit to the fiber length increase which plays a role in the impact strength. Certainly interfacial shear strength of the fiber is the key player in this limiting role. The author observed similar outcome in the previous study on the long glass fiber/PP [16]. Comparing the Izod impact results of the glass/PP [16] with that of corresponding HLFT (i.e., 5, 10 and 20 mm HLFT length) showed a better performance for the HLFT. The results showed 10%, 5.2% and 10.48% increase in the Izod impact strength for the HLFT compared to corresponding glass/PP LFTs, respectively. The

Table 3 Tensile and izod impact performance

Initial LFT fiber length (mm)	Tensile[a] strength (MPa) Glass/PP LFT	Tensile strength (MPa) Hybrid glass/carbon/PP LFT	Tensile[a] modulus (MPa) Glass/PP LFT	Tensile modulus (MPa) Hybrid glass/carbon/PP LFT	Izod impact[a] (kJ/m^2) Glass/PP LFT	Izod impact (kJ/m^2) Hybrid glass/carbon/PP LFT
Neat PP	23.5	–	1061	–	3	–
5	38.51	49.9	1957.3	2725	10.27	11.3
10	40.54	55	2113.4	2905	11.97	12.6
20	43.80	66	2215.6	3379	12.02	13.26

[a] Result adopted from [16]

advantages of the hybridization can also be observed in the impact strength comparison mentioned above, though, the difference may not be so significant. This lower performance in the impact strength comparison can certainly be attributed to the brittle nature of the carbon fiber roving.

The high velocity impact performance of the hybrid LFT was investigated by execution of ballistic impact tests as described earlier. Three high velocity impact regimes were selected for the tests, namely: 144, 205 and 240 m/s. The results for the high velocity impact tests are presented in Fig. 3. The results show a steady decrease in the residual velocity i.e., a better impact performance with increase in hybrid LFT fiber length for all three velocities tested. The results indicate that with the HLFT fiber length increase from 5 to 10 mm and then to 20 mm the residual velocity shows a decrease of 17.6% and 25% for the impact velocity of 144 m/s, respectively. Similar assessment for the 205 and 240 m/s impact velocity reveals only 5.7%, 15.8%, 2.4% and 7.2% decrease in residual velocity for the corresponding HLFT fiber length increase (from 5 to 10 mm and then to 20 mm original fiber length), respectively. The fluctuation in residual velocities as HLFT length increases may be due to the nature of test i.e., very high strain rate and slight inhomogeneity of the HLFT compounds. Furthermore, one can see that, as the impact velocity increases the fiber length in the HLFT losses its significance. This observation is very similar to the result obtained for the Izod impact tests reported above, there, also we witness HLFTs fiber length increase losses its significance.

Impact velocity versus residual velocity behavior for the three velocities tested is presented in Fig. 4. The figure shows near linear behavior for lower impact velocities (144 and 205 m/s) and an approximate nonlinear response at the higher velocity (240 m/s). These linear and nonlinear behaviors are more pronounced in the shorter HLFT fiber length (5 mm). Further study of the Fig. 4 also reveals better impact strength of the HLFT with longer fiber length.

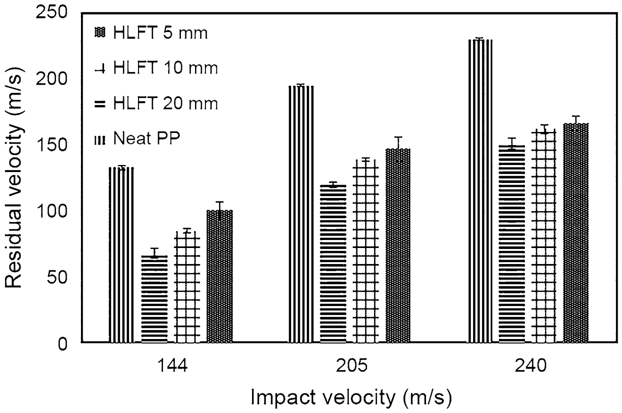

Fig. 3 Impact velocity versus residual velocity for HLFT composite

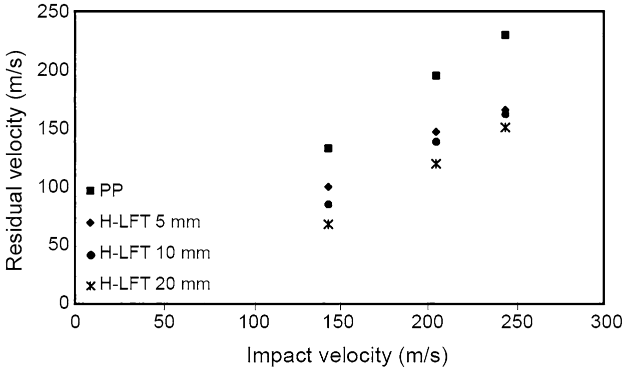

Fig. 4 Impact velocity versus residual velocity behavior for HLFT composite

This better performance is reflected in the energy absorption assessment calculated using Eq. 1 above and presented in Fig. 5. The figure clearly shows a steady increase in energy absorption capacity of the HLFT composite with increase in HLFT fiber length. This increase is consistent in all impact velocities tested.

Comparative assessment of high velocity impact response was made between glass/PP LFT and that of HLFT composite, which the results of this comparison are depicted in Figs. 6 and 7. Impact velocity versus residual velocity comparison for the 5 mm length LFTs presented in Fig. 6 clearly shows better impact performance of the HLFT composite for all three impact velocities tested. Similarly, the same outcome was obtained for 10 and 20 mm LFT length comparison (Fig. 7). This is certainly due to the presence of high strength and stiffness carbon fiber. It must be remembered that in a high velocity impact event five distinct steps exist, namely contact, indentation, penetration, perforation and exit. Each of these steps has a share in energy absorption with the first three taking most of the share. Major roles played in these three steps are tensile strength, stiffness and hardness [17]. Now considering HLFT compound

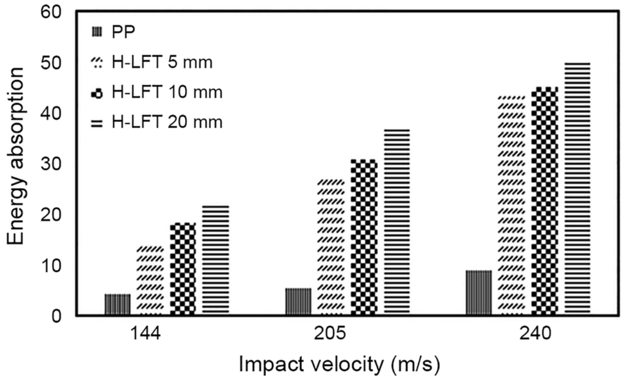

Fig. 5 Energy absorption performance for HLFT composite

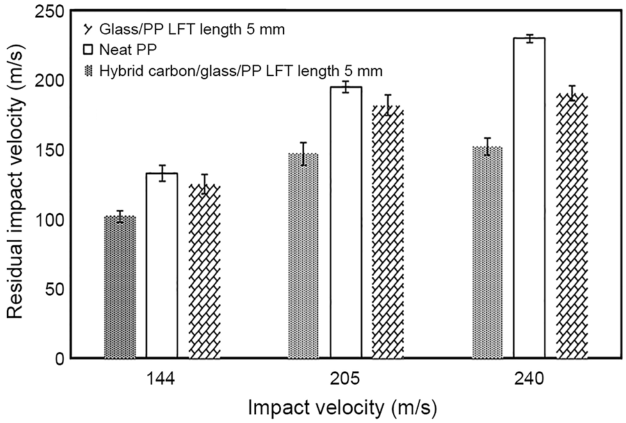

Fig. 6 High velocity impact comparison of glass/PP LFT and HLFT with 5 mm LFT length

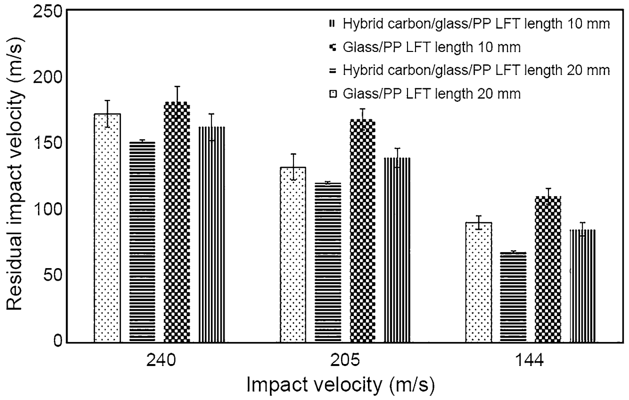

Fig. 7 High velocity impact comparison of glass/PP LFT and HLFT with 10 and 20 mm LFT length

performance in high velocity impact test, one can easily see the reason for higher energy absorption i.e. contribution of carbon fiber presence.

Conclusion

This study sets out to objectively measure and assess the mechanical and high velocity impact performance of hybrid carbon/glass/PP long fiber thermoplastic composites with the fiber length of 5, 10 and 20 mm. The comparison was also made between all tests carried out on HLFT composite with that of corresponding glass/PP LFTs [16]. The following conclusions can be drawn from the results obtained.

1. Hybrid LFT showed higher tensile strength, modulus and Izod impact with increasing fiber length.
2. The higher performance in mechanical tests was more pronounced in longer HLFTs composites.
3. High velocity impact response of HLFT composite also showed higher energy absorbing capacity with increase in fiber length.
4. Comparing the results of the mechanical tests on HLFT with those of the corresponding glass/PP LFTs revealed greater performance and the density difference could emphasize the advantages of HLFT composites.
5. HLFT composite showed better high velocity impact performance than glass/PP LFTs.

References

1. Thomason JL (2009) The influence of fibre length, diameter and concentration on the impact performance of long glass-fibre reinforced polyamide 6,6. Compos Part A Appl S 40:114–124
2. Lin JH, Huang CL, Liu CF, Chen CK, Lin ZI, Lou CW (2015) Polypropylene/short glass fibers composites: effects of coupling agents on mechanical properties, thermal behaviors, and morphology. Materials 8:8279–8291
3. Weidenmann KA, Grigo M, Brylka B, Elsner P, Böhlke T (2017) Time temperature dependence of long fiber reinforced polypropylene manufactured bydirect long fiber thermoplastic process. Int J Chem Mol Nucl Mater Metall Eng 11:13–18
4. Thomason JL, Groenewoud WM (2005) The influence of fibre length and concentration on the properties of glass fibre reinforced polypropylene: 6. the properties of injection moulded long fibre PP at high fibre content. Compos Part A Appl S 27:995–1003
5. Thomason JL (2007) The influence of fibre length and concentration on the properties of glass fibre reinforced polypropylene: 7. Interface strength and fibre strain in injection moulded long fibre PP at high fibre content. Compos Part A Appl S 38:210–216
6. Thomason JL (2008) The influence of fibre length, diameter and concentration on the modulus of glass fibre reinforced polyamide 6,6. Compos Part A Appl S 39:1732–1738
7. He B, Liu H, Leng J, Yang B, Chen X, Fu J, Fu Q (2011) Mechanical properties of long glass fiber-reinforced polypropylene composites and their influence factors. J Reinf Plast Compos 30:222–228
8. Fu SY, Lauke B, Mäder E, Yue CY, Hu X (2000) Tensile properties of short-glass-fiber- and short-carbon-fiber-reinforced polypropylene composites. Compos Part A Appl S 31:1117–1125
9. Kada D, Koubaa A, Tabak G, Migneault S, Garnier B, Boudenne A (2016) Tensile properties, thermal conductivity, and thermal stability of short carbon fiber reinforced polypropylene composites. Polym Compos 39:E664–E670
10. Zhang D, He M, Luo H, Qin S, Yu J, Guo J (2018) Performance of long glass fiber-reinforced polypropylene composites at different injection temperature. J Vinyl Addit Techn 24:233–238
11. Zhang D, He M, Qin S, Yu J (2017) Effect of fiber length and dispersion on properties of long glass fiber reinforced thermoplastic composites based on poly(butylene terephthalate). RSC Soc Chem 7:15439–15454
12. Kumar KS, Bhatnagar N, Ghosh AK (2007) Development of long glass fiber reinforced polypropylene composites: mechanical and morphological characteristics. J Reinf Plast Comp 26:239–249
13. Uawongsuwan P, Yang Y, Hamada H (2015) Long jute fiber-reinforced polypropylene composite: effects of jute fiber bundle and glass fiber hybridization. J Appl Polym Sci 132:1–13

14. Lee DW, Ma S, Lee KY (2013) Electrical and mechanical properties of carbon/glass hybridized long fiber reinforced polypropylene composites. Macromol Res 21:767–774
15. Panthapulakkal S, Raghunanan L, Sain M, KC Birat, Tjong J (2017) Natural fiber and hybrid fiber thermoplastic composites: advancements in lightweighting applications. In: Green composites, 2nd edn. Woodhead Publishing Series in Composites Science and Engineering, pp 39–72
16. Shayan Asenjan M, Sabet SAR, Nekoomanesh M (2019) Long fiber thermoplastic composites under high-velocity impact: study of fiber length. J Compos Mater 53:353–360
17. Zukas JA (1990) High velocity impact dynamics. Wiley-Interscience, Michigan