EFFECT OF FIBER LOADING AND FIBER LENGTH ON MECHANICAL AND THERMAL PROPERTIES OF SHORT CARBON FIBER REINFORCED POLYPROPYLENE COMPOSITE

F. Rezaei*[1], R. Yunus[1], N. A. Ibrahim[2] and E.S. Mahdi[1]

[1]*Department of Chemical and Environmental Engineering, University Putra Malaysia 43400 Serdang, Selangor*
[2]*Department of Chemistry, Faculty of Science, University Putra Malaysia, 43400 Serdang, Selangor*

**Corresponding author email: fateme.rezaei@gmail.com*

Keywords: Short carbon fibers, composites, polypropylene, Izod un-notched impact test, work of fracture (WOF)

Abstract

In this work, short-carbon-fiber-reinforced polypropylene (SCF/PP) composite was prepared with blending and hot-pressing techniques. The tensile and hardness properties and work of fracture (WOF) of this composite were investigated. The tensile strength and modulus of SCF/PP composite were studied taking into account the combined effect of fiber weight fraction and mean fiber length. The composite WOF was studied via the un-notched Izod impact energy. The Izod impact tests were performed with an Izod tester on specimens with un-notches. The WOF of composite was investigated by taking into account the effects of fiber weight fraction and mean fiber length.

Abstrak

Dalam kajian ini, komposit polipropilena bertetulang gentian karbon pendek disedikan melalui teknik tekanan panas dan pengadunan lebur. Sifat kekuatan tegangan dan kekerasan serta kerja patah (WOF) bagi komposit ini akan dikaji. Kekuatan tegangan dan modulus bagi komposit SCF/PP dikaji dengan mengambil kira kombinasi, kesan pecahan jisim karbon dan purata panjang karbon. WOF bagi komposit pula dikaji melalui tenaga hentaman Izod tanpa takuk. ujian hentaman Izod dilakukan menggunakan alat penguji Izod ke atas specimen tanpa takuk-komposit WOF dikaji dengan mangambil kira kesan pecahan jisim karbon dan purata panjang karbon.

Introduction

An important development which takes place in the automotive industry over the past six years is designed to meet the new requirements relating to energy conservation, safety and antipollution. Plastic materials, both reinforced and none reinforced, are potentially well-suited to satisfy these new requirements, but the cost and performance of plastics components depends on the strength and process involved. Carbon fiber reinforced thermoplastics are advanced materials for future high-performance composites. Combination of characteristics such as light-weight, corrosion resistance, low to moderate cost, high thermal stability and easy material processability, make them attractive for many applications especially in automotive industry [1]. High strength, stiffness, and toughness as well as lightness are the most important characteristics of an ideal engineering material. Conventional engineering materials i.e., metals and their alloys are strong and tough, but not light. Certain plastic materials are light but lack strength. Carbon fiber reinforced composites have all the ideal properties, leading to their rapid development and successful use for many applications over the last decade. Our relentless concern on carbon dioxide emissions and petroleum reserves transpire considerable interest in technologies that reduce fuel consumption in passenger cars. In the area of vehicle design, body weight is the most important target for improvement. It has been demonstrated that thermoplastic composites provide a real option for horizontal parts in passenger cars [2-9]. A good case in point is a bonnet, where traditionally a steel skin is used. The material required for this application has to be recyclable, have good impact strength, low weight and high stiffness. It also requires an extremely low coefficient of thermal expansion (CTE) and the ability to bond with steel [10]. Higher utilization of low-density materials such as polymer composites is a pre-requisite for the light weight vehicle of the future. Of all the commodity polymers, polypropylene (PP) is the most attractive for the automotive industry. In the present work, polypropylene (PP) composites reinforced with short carbon fibers (SCF) were prepared by blending and hot-pressing techniques.

Experimental

Materials

The materials employed in this investigation were polypropylene (Titanpro SM950 Polypropylene Copolymer) as the matrix [11] and carbon fiber (Composite Oracle™, Torayca T700S 12K) as the reinforcing fiber [12]. The mechanical and physical properties of these materials are listed in Table1.

Specimen preparation

Chopped carbon fibers were prepared from continuous carbon fiber using universal cutting mill machine (Pulverisette 19) in five sizes: 10, 5, 2, 1, and 0.5 mm. Chopped fibers descended with the help of vacuum operation. The composites were prepared by blending carbon fiber (1-7 wt%) and polypropylene in pellets form using Thermo Haake PolyDrive R600/610.The temperature and the rotor speed were set to 170^oC and 50 rpm respectively. At first, PP pellets were melted for 5 min and then chopped carbon fibers were added to melted PP. All of the specimens were hot pressed using HSINCHU Hot Press Machine. Hot press temperature was set to 170^oC, cooling temperature 60^oC, heating time 5 min, cooling time 3 min and pressure 150×10^4 kg/m^2. The pressing technique is the most common method for making carbon fiber reinforced thermoplastics [13]. Composite sheets (15 × 15 cm) with 1 mm and 3 mm thickness were fabricated.

Table 1 Material Properties

Materials	Tensile strength (MPa)	Tensile modulus (GPa)	Density(g/cm^3)	Diameter(μm)
Carbon fiber	4900	230	1.8	6.8671
Polypropylene	18.35	1.47	0.9	-

Tensile Test

To evaluate the mechanical properties of SCF/PP composites, tensile test was performed. All the specimens with thickness of 1 mm were cut into dumbbell-shaped tensile bars according to the ASTM D638. Tensile properties were determined using 7 replicates for each composition with an Instron 4302 testing machine at a constant cross-speed 5 mm/min and 1 kN load. The yield stress was determined as the first maximum in the stress–strain curves. In this case, the average values were calculated from five runs for each sample.

Hardness Test

Rockwell hardness test of composite were performed using Mitutoyo ATK-600 Hardness Testing Machine, according to the ASTM D785. R scale was chosen with 1.27 cm ball indenter and 98 N minor load and 588 N major load. The specimens were tested 7 times and the average value was obtained from them.

Flexural Test

Flexural tests were carried out according to ASTM D 790-98. The test procedure used was testing method 1 and procedure a (three-point bending system utilizing center loading). The test was conducted using Instron Universal Testing Machine 5566 with a load cell of 5 kN. The cross-speed was set to 3 mm/minute. The span length was set to 70 mm. The specimens were cut in to rectangular sizes with 3 mm thickness, 12 mm width and 124 mm length. Flexural strength and flexural modulus were determined using 7 specimens for different composite formulations.

Izod Impact Test

In order to measure the work of fracture (WOF), the Izod impact test was carried out. Impact bars were obtained by cutting specimens in rectangular shapes. These rectangular specimens are of thickness 3 mm, width 12 mm and length 62 mm according to ASTM D256. Izod impact tests were conducted on an Izod impact tester using 7 replicates for each specimen. The test was carried out with impact energy of 5 J and a span length of 60 mm at 30^{o}C. The average value of un-notched Izod impact energy was obtained from each group of 7 specimens.

Thermogravimetric Analysis (TGA)

TGA was used to determine the thermal stability and degradation of SCF/PP composites. The analysis was conducted by Perkin Elmer TGA -7 from ambient temperature to 500^oC at a heating rate of 10^oC per minute.

Scanning Electron Microscope (SEM)

SEM was employed to study the tensile and impact fracture surfaces of composite samples based on 7 % fiber content with different carbon fiber lengths. They were examined using a LEO 1455 VP SEM analyzer. This test was carried out to determine the dispersion of fiber in the matrix, adhesion between fiber and matrix and to detect the presence of any micro defect in the composite.

Results and Discussion

Tensile properties

The tensile stress–strain curve of pure PP matrix is shown in Figure 1. It exhibits that PP shows a ductile type of curve and the strain of failure is about 487% but SCF/PP composite exhibits a brittle fracture and shows linear deformation at lower stresses and nonlinear deformation at higher stresses. Figure 2 shows the tensile strength as a function of CF weight fraction (wt %) for different sizes of CF in SCF/PP composites. Figure 3 show the tensile modulus of SCF/PP composite. The addition of carbon fibers effectively enhances the ultimate strength of pure PP. It can be seen that the strength and modulus of SCF/PP increased with the increase of carbon fiber sizes.

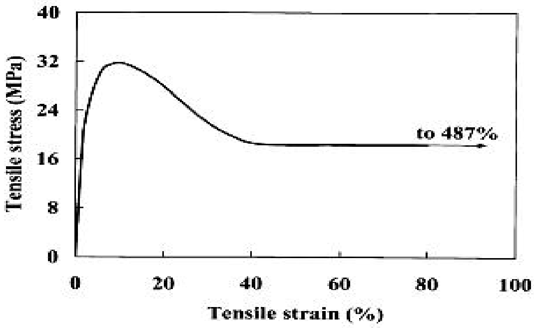

Figure 1: Typical tensile stress–strain curve for the pure PP matrix material.

The tensile strength of SCF/PP composites as a function of CF weight fraction (wt %) for different sizes of CF has shown in Figure 2. As it is expected, the tensile strength of SCF/PP increased by increasing CF loading. It indicates that fiber loading play a major role in the strength of CF composites. This is because carbon fibers have a much higher strength than PP matrix. Strong interfacial bonding between the fillers and the matrix caused efficient stress transfer when strain is applied on a tensile specimen [13].

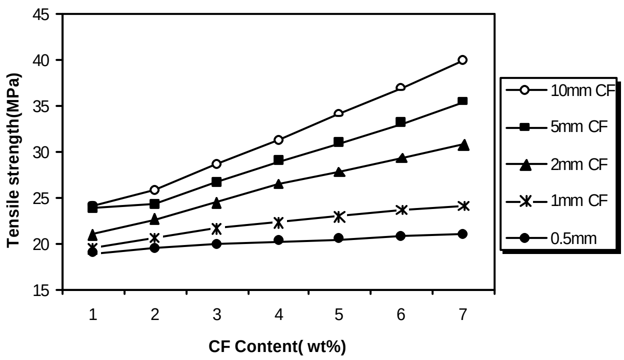

Figure 2: Tensile strength versus fiber weight fraction for SCF/PP composites.

It was also observed that as the fiber length increased, the tensile strength of composites increased too. Longer fibers can tolerate more stress than the shorter fibers, so exhibit higher tensile strength. Figure 3 represent the tensile modulus of SCF/PP composites. The incorporation of CF enhanced the tensile modulus of SC/PP composites compared to unfilled PP (1459 MPa). Furthermore, by increasing fiber length the similar improvement in tensile modulus was observed.

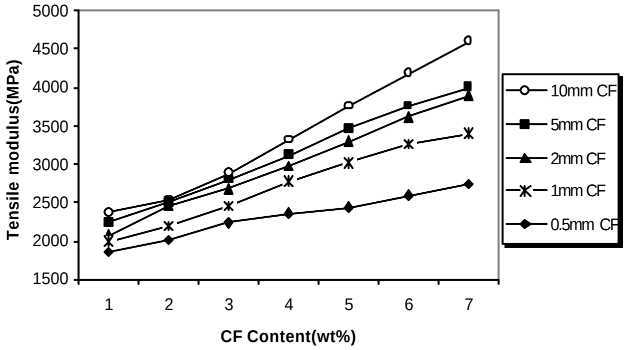

Figure 3: Tensile modulus versus fiber weight fraction for SCF/PP composites.

Hardness Properties

The Rockwell-hardness test results are presented in Figure 4 as a function of CF content (wt %). Hardness is a function of the relative fiber loading and modulus of the composites [14]. Fibers that increase the moduli of composites should also increase the hardness of thermoplastic composites. As the relative fraction of CF in the composite increase, the hardness of composite increase as well. On the other hand, as the size of carbon fiber increases, the hardness index would increase.

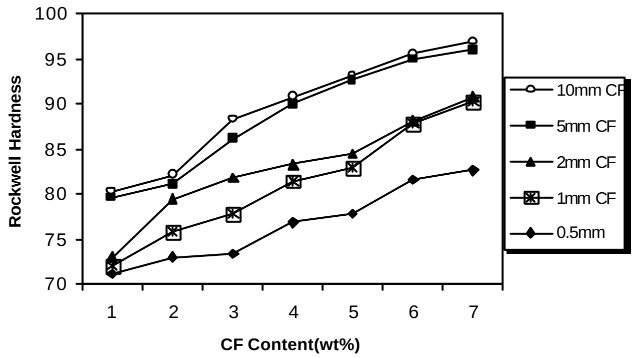

Figure 4: Hardness versus fiber weight fraction for SCF/PP composites.

Izod Impact Properties

The WOF of SCF/PP composites based on the un-notched Izod impact test is presented in Figure 5 and show that the un- notched impact energy increased by the addition of carbon fibers to PP. It indicated that the fibers played a dominant role in terms of fracture energy. On the other hand, the composite impact energy would increase with increased average fiber length. Long fibers can hold greater stress in the PP matrix before break, when load is applied compared to the shorter fiber [15]. Long fibers also exhibit more resistance to crack propagation in the matrix compared to short fibers. The low impact strength of shorter fibers composites may also be due to the presence of too many fiber ends within the composites, which could induce crack initiation, hence increase potential of the composite failure. Stress concentrated at regions around fiber ends, areas of poor adhesion, voids, cracks, notched and other regions where fibers are in contact with one another.

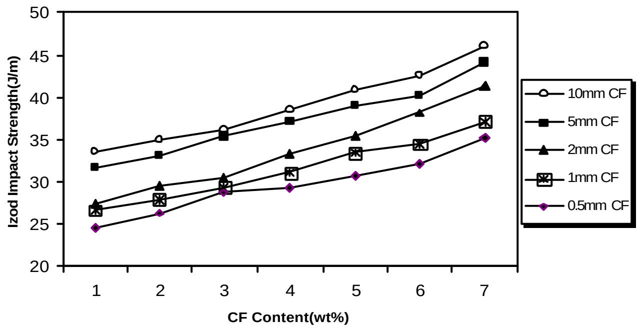

Figure 5: Un- notched Izod impact energy versus fiber weight fraction for SCF/PP composite.

Flexural Properties

The flexural properties of SCF/PP are given in Figure 6 and Figure 7 as a function of carbon fiber content. The flexural strength and flexural modulus increased as the carbon fiber weight fraction increased. In addition, flexural strength and flexural modulus increased with the increase in carbon fiber size in the composite. It indicated that besides fiber loading, fiber length affected the properties of CF composites too. SCF/PP composite with longer carbon fiber bearded a high load, due to this fact that longer carbon fiber can tolerate more stress than shorter ones, resulting in a high flexural strength and modulus. The highest flexural strength and modulus was achieved at 79.1 MPa and 8375 MPa respectively for SCF/PP composites with 10 mm CF length and 7% loading.

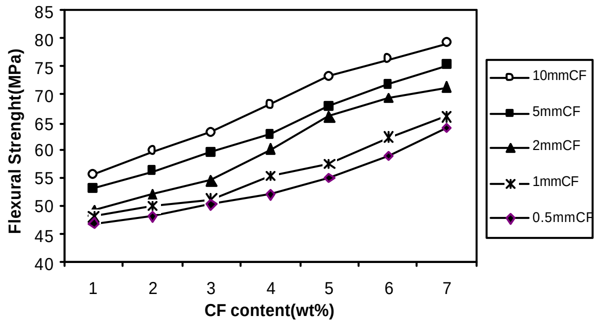

Figure 6: Flexural strength versus fiber weight fraction for SCF/PP composites.

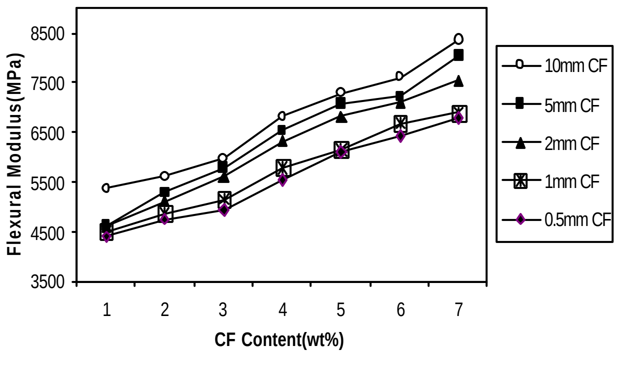

Figure 7: Flexural modulus versus fiber weight fraction for SCF/PP composites.

TGA

Thermal stability of CF composites for automotive application is necessary in determining their end use. The effect of different lengths of CF on the thermal degradation of PP was investigated. A TGA curve of SCF/PP composites (7% fiber content and 10 mm fiber length) is given in Figure 8. A sudden drop in the mass of the sample indicated the thermal degradation of the material. The materials started to thermally degrade at 300^{o}C, and decomposed at 472 °C where substantial loss in their weights was observed. The urve also shows that thermal degradation began to occur only after the materials have absorbed certain amounts of heat energy. The heat initiated the degradation processes and the breaking down of the fibers and matrix structure by causing molecular chain ruptures or scission. Details of the thermal degradation of PP, and SCF/PP composites with different CF lengths are given in Table 2. According to these data, the introduction of CF fibers to the PP matrix, in general, increased the degradation temperature of the composites. This is due to the fact that heat absorption capacity of CF is higher than PP. As the length of fibres increased, the fibers in the composites absorbed more heat, thus higher temperature was therefore required to achieve the threshold energy for commencement of the degradation process. Thus, as CF lengths increased, there was a shift upward of the degradation temperature. The introduction of fillers into polyalkanes results in an increase of the thermal stability of the polymer [16].

Table 2: Percentage weight loss in SCF/PP composites at different temperatures

Wt. Loss	PP	Degradation Temperature SCF/PP Composites				
%		0.5mm	1mm	2mm	5mm	10mm
10	362	400	403	406	410	415
20	378	409	414	418	420	422
30	399	421	425	426	428	432
40	404	424	427	428	430	440
50	413	429	430	431	432	445
60	425	432	433	435	436	450
70	428	437	441	442	445	456
80	434	441	448	451	454	461
90	445	450	453	457	460	465
93	441	463	464	468	472	473

Incorporated fillers reduced the chain mobility in the absorption and boundary layers. This led to a decrease in the tension induced to the carbon-carbon chain by the thermal excitation and since majority of bond breaking is via this mode, less degradation occurs. Hence, the grafting of macromolecules onto the filler surface and the formation of spatial chemical structures in the filled polymer improved the thermal stability.

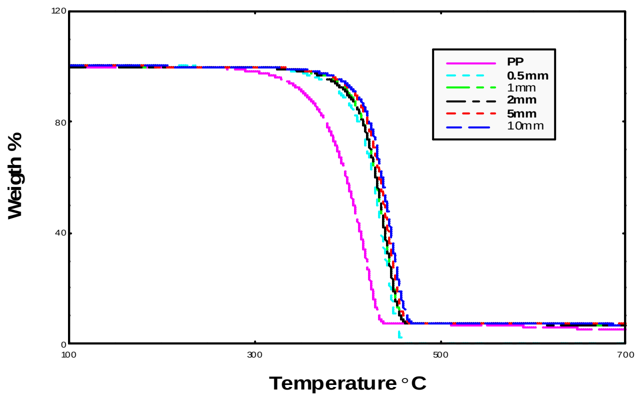

Figure 8: TGA curves of PP Matrix and SCF/PP composites with 7% fiber content and 10 mm fiber length.

Surface morphology

Figure 9 and Figure 10 show the SEM micrographs of the fracture surface of SCF/PP composites after tensile and impact test with 400x magnifications. It can be seen from Figure 9 that the fibers aligned in different directions and randomly oriented. No gap between the fiber and the polymer matrix can be seen. The cracks on fiber ends support the fact that the fibers have undergone more breakage rather than pull out, which affirmed a better interfacial strength. A fiber-matrix debonding is observed near the fracture surface.

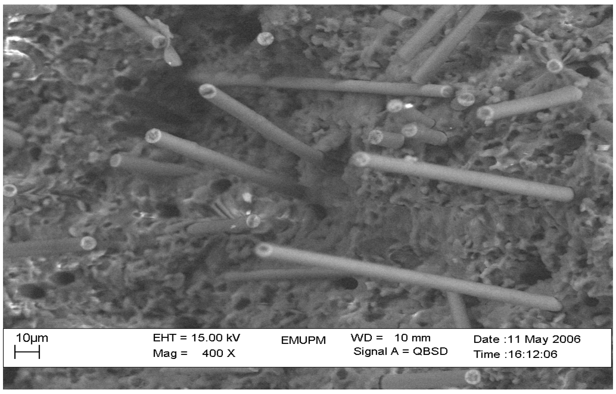

Figure 9: SEM micrograph of tensile fracture of the SCF/PP composite with 7 wt% carbon fiber.

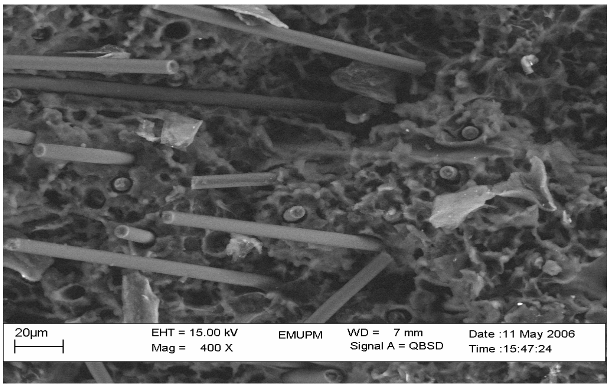

Figure 10: SEM micrograph of impact fracture of the SCF/PP composite with 7 wt% carbon fiber.

Figure10 shows some regions which PP matrix has undergone the plastic deformation under load before complete fracture.

Conclusion

SCF/PP composites with five different sizes of carbon fiber were fabricated by compression technique. Tensile properties, hardness and impact properties of SCF/PP were investigated. The results have shown that composite strength and stiffness increased with the increase of carbon fiber content. The hardness results showed that by increasing of carbon fiber to pure PP the hardness of composite increased as well. The impact results show that the addition of SCF to PP considerably enhance the un-noched Izod impact energy. All of above properties increased as the CF length increased.

Acknowledgements

The authors are indebted to SIRIM and MOSTI (Ministry of Science, Technology and Innovation) for providing financial support for this project.

References

1. L.A. Carlson, 1991. Thermoplastic composite materials. Florida Atlantic University
2. MG. Bader, JF. Collins, 1983. The effect of fibre-interface and processing variables on the mechanical properties of glass-fibre filled nylon 6. Fibre Sci Technol **18**:217–31
3. H. Bijsterbosch, RJ. Gaymans, 1995. Polyamide 6-long glass fiber injection moldings. Polym Compos **16**: 363–9
4. L. Biolzi, L. Castellani, I. Pitacco, 1994. On the mechanical response of short fiber reinforced polymer composites. J Mater Sci **29**: 2507–12
5. PT. Curtis, MG. Bader, JE. Bailey, 1978. The stiffness and strength of a polyamide thermoplastic reinforced with glass and carbon fibers. J Mater Sci;**13**: 377–90
6. J. Denault, T. Vu-Khanh, B. Foster, 1989. Tensile properties of injection molded long fiber thermoplastic composites. Polym Compos **10**: 313–21
7. S.-Y. Fua,, B. Laukeb, E. Ma¨derb, C.-Y. Yuea, X. Hua, 2000. Tensile properties of short-glass-fiber- and short-carbon-fiber-reinforced polypropylene composites Composites: Part A **31**: 1117–1125
8. R. Weiss, 1991. Fabrication techniques for thermoplastic composites, Cryogenics, 319-322

9. S.Y. Fua, B. Lauke, E. MaÈder, X. Hu , C.Y. Yue, 1999. Fracture resistance of short-glass-fiber-reinforced and short-carbon-fiber-reinforced polypropylene under Charpy impact load and its dependence on processing; Journal of Materials Processing Technology **89-90**:501-507
10. Reinforced Plastics© Copyright 2005, Elsevier Ltd, 2005. www.reinforcedplastics.com
11. http://www.titangroup.com/Products/TITANPRO_English.asp
12. http://www.composite-oracle.com/materials.asp?q=2
13. Ferrigno, T. 1985. Principles of Filler Selection and Use. In Handbook of Fillers for Plastics, H. Katz and J. Milewski, ed.: Van Nostrand Reinhold Co. New York, pp 8-61.
14. Donnet, J. B., Wang, T. K., Rebouillat, S., Peng, J. C. M. eds. 1998. Carbon fibers, **3**rd ed. Marcel Dekker, New York, p 463.
15. Strong, A. B. 2000. Polymer Composites. In Plastics: Materials and processing 2nd ed. prentice Hall. New Jersey. pp 811
16. Bryk, M.T. 1991. Degradation of Filled Polymers: High Temperature and Thermal-Oxidative Process. New York: Ellis Horwood