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Effect of Geometry and Loading Fractions on Energy Absorbing Properties of Fiberglass Polymer Composite Under Quasi-Static and Low-Velocity Impact Loadings

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ABSTRACT: The focus of this study is to experimentally investigate the mechanical properties of fiberglass reinforced composite with various aspect ratios and loading fractions in the quasi-static and low-velocity impact loading conditions. In this study, short fiberglass reinforced polycarbonate composite materials were fabricated via a solution mixing method and characterized for their tensile properties by varying both fiberglass loading fraction and aspect ratio. The tensile properties including tensile toughness of the fiberglass reinforced composites were characterized and compared. It was observed in this study that the toughness of the composite was dramatically improved whereas the tensile strength and Young's modulus were moderately enhanced over the neat polymer, which were measured to be only up to 15% and 70% increase, respectively. The low-velocity impact behaviors of the fiberglass composites were also investigated and compared to the tensile toughness of the corresponding composites. Besides, the effect of thickness on their low-velocity impact properties was investigated. © 2014 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2014**, *131*, 40821.

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INTRODUCTION

Fiberglass reinforced polymer composites are widely used in various engineering applications including hand-held devices and printed circuit board (PCB) because of their low-cost, yet fairly good mechanical properties, such as tensile strength and Young's modulus.[1] Although the fiberglass reinforced composites have been used for a while, it is still necessary to optimize the fiberglass' geometry or loading fraction in order to meet the rapidly growing needs on lightweight and high strength. Typically, the mechanical properties including tensile strength and toughness are characterized under quasi-static loading conditions.[2] Numerous reports on the study of the structure–property relationship in the short fiberglass composite materials are available. It was well-reported that overall properties of a short fiber composite are determined by the fibers' orientation, aspect ratio, volume fraction and/or the interface between fiber and matrix.[3–7] In particular, orientation and aspect ratio of the short fiber are known to be key parameters on tensile properties of the short fiber-reinforced composites among other parameters. Fu et al. studied on the tensile properties of short fiberglass reinforced polypropylene composites by varying the fiber loading fraction: the relationship between the fiber efficiency factors and various fiber volume fractions. Their study claimed that the fiber efficiency factor is decreased when the fiber volume fraction is increased, as well as the fiber efficiency factor for the composite modulus becomes much greater than that for the composite strength.[3] Jiang et al. reported that if the mean aspect ratio of a short fiber is used in predicting the mechanical properties of the composite with analytical models, it often gives rise to a significant error in calculating the accurate mechanical properties particularly when the mean aspect ratio distribution is not symmetrical.[4] In spite of the significant effort on the structure–property study, it still lacks understanding of the energy absorbing properties including the tensile toughness of the composites with respect to the fiberglass' microstructure such as aspect ratio or volume fraction. Low-velocity impact test is also conducted to investigate the energy absorbing

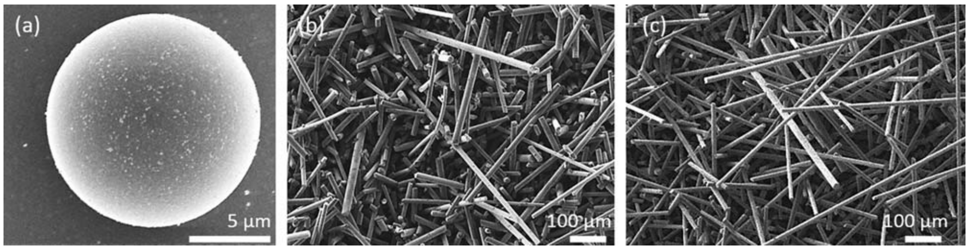

Figure 1. The different types of fiberglass reinforcement particles based on their aspect ratios. (a) Aspect ratio of 1, (b) aspect ratio of 14, and (c) aspect ratio of 21.

properties of the composites, which can give rise to the understanding of dynamic deformation and failure behaviors.[8–10] Hassan et al. experimentally investigated the effect of fiberglass on low-velocity impact properties and reported that the longer fibers tend to be broken in a brittle manner whereas the shorter fibers exhibit more ductile-like failure during the impact loadings since more fracture energy is consumed through the fiber pull-out failures.[11]

It will be important to have the understanding of the relationship between tensile toughness and impact behavior of the fiberglass composites in analysis and design of short fiber-reinforced composites. However, very few reports exist on such investigation. Therefore, the focus of this study is to establish and develop a better understanding of the relationship between tensile toughness and low-velocity impact properties of the fiberglass composites by varying the fiber's aspect ratio and loading fraction. We selected SiO_2 particle (aspect ratio, AR = 1) and fiberglass (AR = 14 and 21) as fillers while polycarbonate (PC) as a matrix material to fabricate the fiberglass polymer composites with the several combinations of an aspect ratio and a loading fraction. The tensile properties were characterized under quasi-static loading and compared with the analytical modeling. In addition, low-velocity impact test was conducted for the fiberglass composites down-selected among the combinations of the aspect ratio and the loading fraction investigated in this study. The effect of thickness on the impact properties was also investigated. To the best of our knowledge, no detailed investigation on relationship between tensile toughness and impact properties of short fiber composites has been demonstrated yet, and is an important contribution to the literature on fiber-reinforced composite materials.

EXPERIMENTAL

Particulate Composite Fabrication

In order to fabricate fiberglass reinforcement polymer composites, the PC granules with an average diameter of 3 mm from Goodfellow (Oakdale, PA) were used as a matrix material. The spherically shaped SiO_2 particles (glass beads) with the aspect ratio of 1 and the diameter of 10 µm as the reinforcement were obtained from ABC nanotech (South Korea). Also, the rod-shaped fiberglass particles with two aspect ratios of 14 and 21 were provided from Fibertec (Bridgewater, MA). They are unsized and their average fiber length are 140 and 210 µm (Fibertec product # 3016 and 3004), respectively. All glass beads and fiberglass have approximately 10–12 µm in diameter. So, we called them AR = 14 and 21. The SEM images of the SiO_2 and fiberglass particles are seen in Figure 1 showing the structural morphology.

The solution mixing method was employed to fabricate neat PC and fiberglass reinforcement PC composites. In preparation of the PC matrix, 1.5 g of PC granules was dissolved in Tetrahydrofuran (THF) for about 10 min using a sonicator (Misonix Ultrasonic Liquid Processor). The desirable weight loading fractions (1, 3, and 5 wt %) of the fiberglass were added to the each vial of PC matrix, and then they were sonicated again to disperse the fibers in the solution. That solution was mixed with methanol, which yielded a precipitate, and that precipitate was put into a mold to create the samples. Note that more details on the fabrication process were found in our earlier work.[12] Both tensile and low-velocity impact test specimens were prepared via a compressive molding technique. The geometry and dimensions of the tensile specimens are chosen according to the ASTM D638 Type V, while the impact specimens are in a square shape (2.5 inch × 2.5 inch) with the thickness of 1 mm or 2 mm.

Characterization of Tensile Properties and Debonding Stress

The tensile properties, such as Young's modulus, tensile strength, and tensile toughness, were characterized. All the fiberglass reinforced polymer composites were tested using the Instron Electropulse E3000 with an acoustic emissions sensor (Physical Acoustics Corporation). While the tensile testing was being performed, the acoustic emission (AE) events were being monitored. The debonding stress was determined by taking the corresponding tensile stress value when the greatest number of AE events was counted during the test. The corresponding stress is called as "global debonding stress (GDS)" in this study.[13]

The AE technique is often used to monitor the fiber breaks and/or identify failures including debonding in short fiber-reinforced composites.[14–17] For the GDS measurement, a single sensor mode was applied to the acoustic emission system, and a transducer was directly attached to the tensile specimen's grip area. During the tensile testing, both tensile and acoustic emission events were monitored and simultaneously recorded.[13] At least nine specimens for the fiberglass composites were tested for three different aspect ratios (AR = 1, 14, and 21) and the composites at least three different weight loading fractions (1, 3, and 5 wt %) were tested for each aspect ratio. The numbers of acoustic emission events in a time interval of 0.01 s were counted corresponding to the applied stress, and the test results are fitted with a normal distribution function. The conditions for all tests were the same. All tests were performed at room

Table I. Physical and Elastic Properties of Each Constituent to Predict the Modulus of the Particulate Composites Using Analytical Models

Materials	Bulk density (g/cm^3)	Young's modulus (GPa)	Poisson ratio
Polycarbonate	1.2	1.81	0.37
SiO_2 particle	2.2	69.0	0.17
Fiberglass	2.6	75.0	0.22

temperature and each polymer composite was placed under uniaxial loading at a constant strain rate (0.5 mm/s). The median of each tensile property are taken to be analyzed and compared in this study.

Low-Velocity Impact Test

The low-velocity impact test was executed, which was driven by the penetrator's gravity and continued until the impact specimen was completely penetrated through its thickness. The Instron Dynatup 9250HV drop tower was used for the impact testing. A 12.8 kgf of impactor with a 12.7 mm in diameter and a hemispherical tip was used to penetrate all impact specimens. The corresponding impact energy and velocity in the testing are 63 J and 3.0 m/s, respectively. Each specimen was held by a 38 mm of diameter adapter plate. At least three specimens for each composite were tested and all the tests were performed at room temperature and atmospheric pressure.

ANALYSIS

Spherically Shaped Particle Reinforced Composites

The elastic modulus of particulate polymer composites can be analytically estimated with the elastic properties of its constituents: particles and matrix. In case of the spherically shaped particles, such as SiO_2 (glass bead (AR = 1)), the Young's modulus of the composites depends on the modulus of the constituents, loading fraction, and size of the particles. Several empirical or semi-empirical micromechanics models have been introduced to predict the modulus of the particulate composites. Among the analytical models, Kerner's model is found to predict the modulus reasonably well particularly when the particle is much stronger than the matrix material ($E_p >> E_m$).[18,19] The model can be expressed as shown in eq. (1), where E_c and E_m are Young's modulus of particulate composite and polymer matrix, respectively, and V_p and υ_m are volume fraction of particle and Poisson ratio of matrix, respectively. The detailed physical and elastic properties of the materials are listed in Table I.[12,20]

$$\frac{E_c}{E_m} = 1 + \frac{V_p}{(1-V_p)}\frac{15(1-\nu_m)}{(8-10\nu_m)} \tag{1}$$

Short Fiberglass Particulate Composites

Since the short fibers are randomly oriented in the fiber-reinforced composites, such composite is assumed to be a nearly isotropic material. The Young's modulus of the fiber-reinforced composites can be estimated with the Halpin–Tsai model that is known to be well-established for randomly oriented discontinuous short fiber composites:

$$\frac{E_c}{E_m} = \frac{3}{8}\left[\frac{1+2(l_f/d_f)\eta_L V_f}{1-\eta_L V_f}\right] + \frac{5}{8}\left[\frac{1+2\eta_T V_f}{1-\eta_T V_f}\right] \tag{2}$$

$$\eta_L = \left[\frac{(E_f/E_m)-1}{(E_f/E_m)+2(l_f/d_f)}\right] \tag{3}$$

$$\eta_T = \left[\frac{(E_f/E_m)-1}{(E_f/E_m)+2}\right] \tag{4}$$

where E_f and V_f are Young's modulus and volume fraction of short fiber, and l_f and d_f are length and diameter of fiber, respectively.[15,21] Two different aspect ratios ($AR = l_f/d_f$ = 14 and 21) of fiberglass were investigated in this study. The used physical and elastic properties of each constituent are shown in Table I.[12,20]

RESULTS AND DISCUSSION

Tensile Properties and Debonding Stress

Figure 2 compares the tensile test results including the tensile strength, Young's modulus, tensile toughness, and the ratio of GDS over tensile strength for the fiberglass reinforced composites. The various loading fractions (1, 3, and 5 wt %) and three different aspect ratios (AR = 1, 14, and 21) of the fiberglass for each weight fraction were investigated. It was seen in Figure 2(a) that the tensile strength of all the composites was increased with 1 wt % of fiberglass or SiO_2. However, as the weight fraction reaches 3 wt %, both composites with the aspect ratio of 1 (AR1) and 21 (AR21) exhibit a decrease in the tensile strength. For the composite with the aspect ratio of 14 (AR14), the tensile strength was decreased after the weight fraction reaches 5 wt %, which is a more or less similar response to the other composites. The AR21 composites with 1 wt % show the greatest improvement in the tensile strength among other composites and more than 15% increase over the neat PC [Figure 2(a)]. The weight fraction of the AR21 composites was further extended up to 40 wt %. It was observed that the tensile strength was inversely proportional to the fiberglass' loading fraction. Interestingly, as the weight fraction increases, the Young's modulus response of both AR1 and AR14 composites was similar to the tensile strength response [Figure 2(b)]. In a sharp contrast, the AR21 composites show an increase in the Young's modulus with the increase of the weight fraction up to 40%, indicating approximately 70% enhancement over the neat PC [Figure 2(b)]. The toughness is considered to be one of energy absorbing properties, which is closely related to the material's ductility. The toughness behavior of the composites is similar to the behavior of the tensile strength in the composites with all three different aspect ratios [Figure 2(c)]. Very interestingly, however, the AR21 composite with 10 wt % of the fiberglass exhibits a dramatic improvement in the tensile toughness, showing approximately 1500% greater than one of the neat PC. However, after the loading fraction reaches 20 wt %, the toughness sharply dropped and close to the one of the neat PC. Although a further study is needed to have better understanding of the tensile behavior of the AR21 composites, it can be explained, at least partially, with the debonding stress of the composites.

Figure 2(d) shows the ratio of the GDS over the tensile strength for the composites with respect to the loading fraction. It was

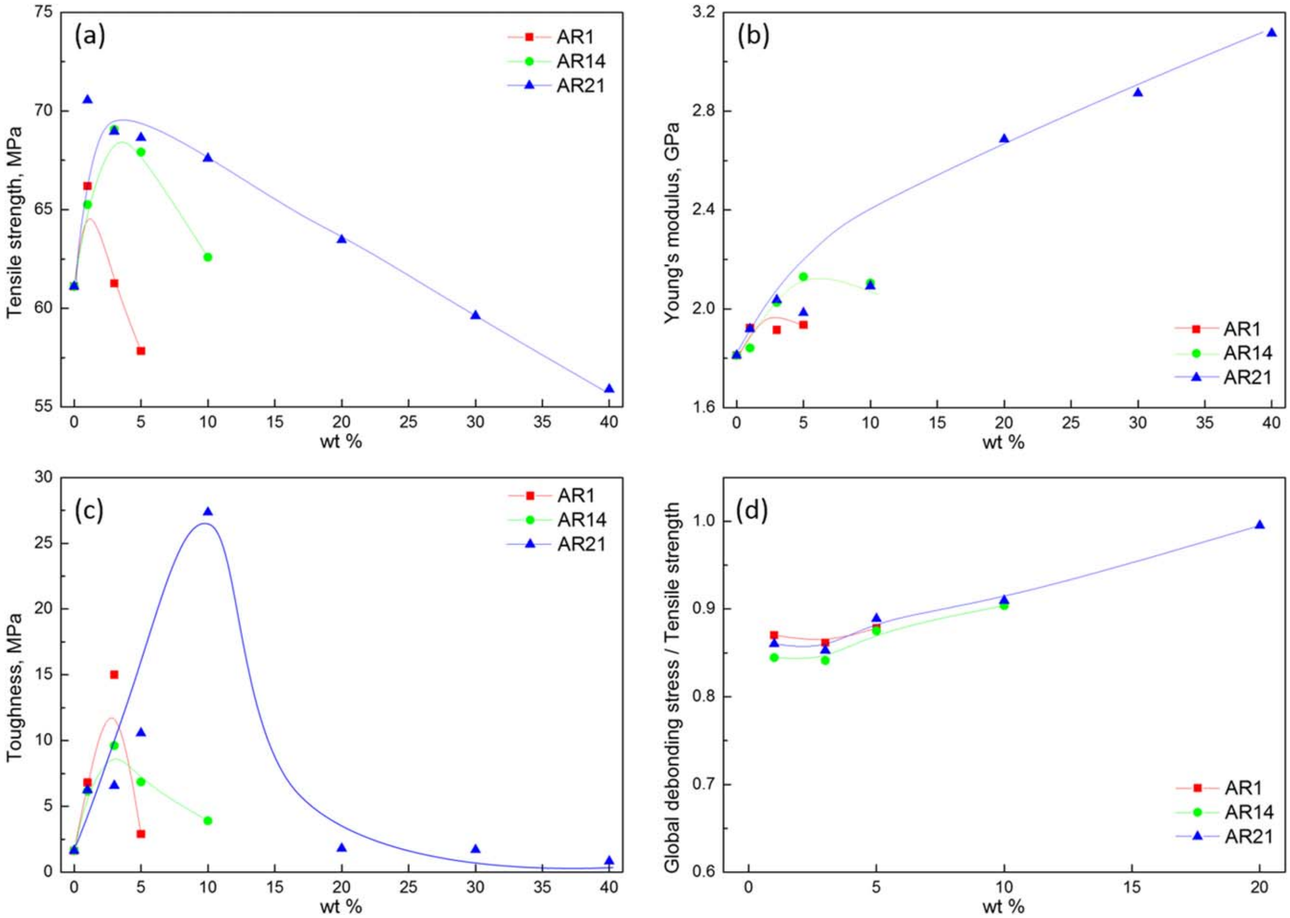

Figure 2. The tensile test results. (a) Tensile strength, (b) Young's modulus, (c) tensile toughness, and (d) global debonding stress/tensile strength of fiberglass polycarbonate composites with respect to fiberglass loading fraction and the aspect ratio. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

observed that the overall response in the ratio of GDS/tensile strength is increasing as the loading fraction increases. Given that the GDS is assumed to be the same for any combination of the aspect ratio and loading fraction, the increase in the ratio can result from the decrease in the tensile strength of the composites. Consequently, the observed toughness enhancement in the AR21 with the loading fraction of 10 wt % disappears as the weight fraction further increases, because the corresponding tensile strength proportionally decreases, which can change the failure behavior from ductile to brittle.

The Young's modulus of both analytical modeling and experimental data are compared to each other, as summarized in Table II. As expected, the analytical modeling results are found to be linearly proportional to the fiberglass' loading fraction, and the prediction shows a pretty good agreement with the

Table II. The Young's Modulus Data Values Obtained from Experiment Versus Those Calculated Using Analytical Models

	Aspect ratio of 1		Aspect ratio of 14		Aspect ratio of 21	
Weight fractions (wt %)	Experimental (GPa)	Analytical (GPa)	Experimental (GPa)	Analytical (GPa)	Experimental (GPa)	Analytical (GPa)
1	1.92	1.83	1.84	1.88	1.92	1.89
3	1.92	1.88	2.03	2.02	2.04	2.06
5	1.94	1.93	2.13	2.16	1.98	2.23
10			2.11	2.55	2.09	2.68
20					2.67	3.71
30					2.87	4.97
40					3.12	6.52

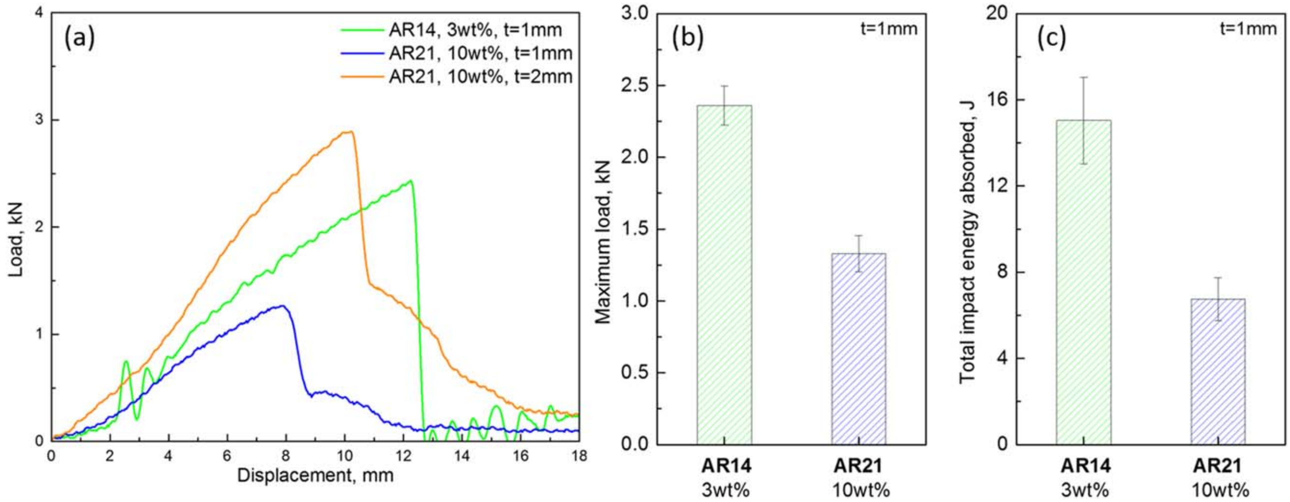

Figure 3. The low-velocity impact test results. (a) Load–displacement curve and (b) maximum load: the bar graph shows the results of the maximum loads of the polymer composites with the aspect ratio of 14 and 21 at 3 wt % and 10 wt %, respectively. (c) Total impact energy absorbed: the bar graph shows the total impact energy absorbed of the polymer composites with the aspect ratio of 14 and 21 at 3 wt % and 10 wt %, respectively. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

experimental data up to 5 wt % loading fraction for all the composites along with the three different aspect ratios. This could indicate that all three composites (AR1, AR14, and AR21) with such low loading fractions would have well dispersion and uniform distribution of the reinforcements. However, the Young's modulus values begin to show a deviation between the modeling and experiment after the loading fraction reaches 10 wt %. These results can imply that the dispersion quality of the fiberglass may not be able to be maintained in the composites and the aggregation may be formed at higher loading fractions.[12]

Low-Velocity Impact Response

It is known that the impact resistance of a material is also one of the energy absorbing properties like tensile toughness. The low-velocity impact testing was conducted to investigate the relationship between the tensile toughness and the impact resistance. Only two composites of AR14 (at 3 wt %) and AR21 (at 10 wt %) were selected in this study, which exhibit the greatest tensile toughness during the tensile testing. The impact specimen with a thickness of 1 mm for each composite was penetrated as described earlier. It was observed in the low-velocity impact test that the AR14 composites exhibit a typical brittle behavior during penetration, while the AR21 composites clearly show a ductile behavior [Figure 3(a)]. Unexpectedly, it was seen in Figure 3(b) and (c) that the AR14 (3 wt %) composites, which showed far less toughness than one of the AR21 (10 wt %) under quasi-static loading, outperform the low-velocity impact properties having the greater maximum load (23 kN) as well as higher total impact energy absorbed (15 J). These impact results could indicate that there is no obvious relationship between the tensile toughness under quasi-static loading and the low-velocity impact properties in the fiberglass composites investigated in this study.

The impact testing was further extended to investigate the effect of thickness on the low-velocity properties for the AR21 (10 wt %) composite, which has much greater ductility index (0.249). Note that ductility index is often used to evaluate the energy absorbing capability since the propagation energy can be translated into irrecoverable dissipated energy. The AR21 composites with a thickness of 2 mm were also tested under low-velocity impact loading. Very interestingly, the 2 mm thick AR21 composite displays a significant improvement in all low-velocity impact properties including the maximum load, deflection at break, total impact energy absorbed, and ductility index over

Table III. Comparison of the Mechanical Properties of the Polymer Composites for the Low-velocity Impact Test at Different Weight Fraction

Fiberglass aspect ratio	AR14	AR21	AR21
Weight fractions (wt %)	3	10	10
Thickness (mm)	1	1	2
Maximum load (kN)	2.36 ± 0.14	1.33 ± 0.13	3.00 ± 0.15
Deflection at break (mm)	11.59 ± 1.31	8.30 ± 0.82	10.62 ± 0.54
Initiation energy, A (J)	14.08 ± 2.35	5.47 ± 1.24	16.12 ± 1.73
Propagation energy, *B* (J)	0.957 ± 0.364	1.276 ± 0.497	5.573 ± 0.591
Total impact energy, *A* + *B* (J)	15.04 ± 2.01	6.75 ± 1.01	21.69 ± 1.14
Ductility index, *B*/*A*	0.072 ± 0.041	0.249 ± 0.118	0.350 ± 0.074

the 1 mm thick composite. More than 330% increase in propagation energy for the 2 mm thick composite was measured compared to the 1 mm thick composite. The detailed impact properties of the composites are summarized in Table III.

CONCLUSIONS

We compared the tensile properties of short fiberglass polycarbonate composites by varying the aspect ratio and the loading fraction in order to highlight the effect of the fiber microstructure on energy absorbing properties. It is seen that there is no significant toughness enhancement observed for the AR1 and AR14 at each loading fraction. In contrast, the AR21 composites at 10 wt % result in a dramatic improvement (more than 1500%) in the tensile toughness compared to the neat PC. However, as the weight fraction was further increased, although the Young's modulus was increasingly improved, the toughness of the AR21 composites began to decrease. This might be attributed to the decrease in the tensile strength resulting from the fiberglass aggregation at higher loading fractions. Note that the Young's modulus was measured within the linear elastic region, which is relatively low strain region. Very interestingly, it was observed in the low-velocity impact testing that the AR14 (at 3 wt %) composites show a brittle failure behavior, whereas the AR21 (at 10 wt %) composites display a typical ductile failure. Although the AR21 composites show much higher tensile toughness over the AR14 under quasi-static loading, much greater maximum load and higher total impact energy absorbed were seen in the AR14 composites. Therefore, there is no obvious relationship between the tensile toughness under quasi-static loading and the low-velocity impact properties in the fiberglass composites in this study. For the AR21 composites, the 2 mm thick composites result in a significant enhancement in the impact properties over the 1 mm thick composites. It could be attributed to the energy dissipated capability, which is often represented by the ductility index. Typically, the materials that experience a ductile failure during low-velocity impact penetration are shown to have higher ductility index and correspondingly better low-velocity impact properties. A further study is needed to have better understanding of the effect of thickness on the impact properties, however.

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