Arab J Sci Eng (2014) 39:9049–9056
DOI 10.1007/s13369-014-1409-8

RESEARCH ARTICLE - MECHANICAL ENGINEERING

Investigation of the Effect of Glass Fiber Content on the Mechanical Properties of Cast Polyamide

Hamdullah Çuvalci · Kadir Erbay · Hüseyin İpek

Received: 2 December 2013 / Accepted: 31 August 2014 / Published online: 8 November 2014

Abstract In this study, a series of cast polyamide-based composite materials were produced by injection molding process. In the production of composite materials, cast polyamide and short glass fiber were used as matrix and reinforcement materials, respectively. The specimens obtained from composite materials having different fiber content were tested to determine tensile and impact strength, modulus of elasticity, tensile elongation and density of composites. In addition, scanning electron microscopic studies were carried out on the fracture surfaces of impact test specimens. It was observed that mechanical properties of composites such as tensile strength and modulus of elasticity increased when the fiber volume content is increased up to 35 %. However, these properties decreased at the fiber content higher than that of 35 %. Moreover, tensile elongation and impact energy values were decreased when the fiber content was increased. In addition, the fiber efficiency factor increased with the increasing fiber content up to 35 %, and after this point, it decreased with the increasing fiber content. On the other hand, it was observed that the fiber efficiency factor for modulus of elasticity was higher than that of the tensile strength. Consequently, it was observed that adding short glass fiber up to 35 % was an effective method to improve mechanical properties of cast polyamide-based composites.

Keywords Cast polyamide · Short glass fiber · Fiber volume fraction · Mechanical properties

H. Çuvalci (✉) · K. Erbay · H. İpek
Metallurgical and Materials Engineering Department, Karadeniz Technical University, Trabzon, Turkey
e-mail: hcuvalci@ktu.edu.tr

الخلاصة

تم - في هذه الدراسة - إنتاج سلسلة من مصبوب البولي أميد القائم على المواد المركبة بوساطة عملية حقن الصب ، حيث تم في إنتاج المواد المركبة استخدام مادة البولي أميد وألياف الزجاج القصيرة كمواد للقالب والتعزيز على التوالي. وتم اختبار العينات التي تم الحصول عليها من المواد المركبة في وجود محتوى ألياف مختلف لتحديد قوة الشد والرص، ومعامل المرونة ، واستطالة الشد وكثافة المواد المركبة. بالإضافة إلى ذلك ، أجريت دراسات المجهر الإلكتروني على السطوح المكسرة من عينات اختبار الرص. ولوحظ أن الخواص الميكانيكية للمواد المركبة مثل قوة الشد ومعامل المرونة زادت عند زيادة محتوى حجم الألياف حتى 35٪. غير أن هذه الخصائص قد انخفضت عند محتوى ألياف أعلى من 35٪. وقد انخفضت ، علاوة على ذلك ، استطالة الشد وقيم طاقة الرص عندما تمت زيادة محتوى الألياف. وبالإضافة إلى ذلك ، فقد زاد عامل كفاءة الألياف مع زيادة محتوى الألياف حتى 35٪ ، ولكنه بعد هذه النقطة انخفض مع زيادة محتوى الألياف. ولوحظ من ناحية أخرى أن عامل كفاءة الألياف لمعامل المرونة كان أعلى من قوة الشد. ونتيجة لذلك، لوحظ أن إضافة الألياف الزجاجية القصيرة حتى 35٪ كان وسيلة فعالة لتحسين الخواص الميكانيكية من مصبوب مادة البولي أميد القائم على المواد المركبة.

1 Introduction

Short-fiber-reinforced polymer (SFRP) composites are very attractive because of their ease of fabrication, economy and superior mechanical properties [1–5]. In general, a high fiber content is required in order to achieve a high-performance SFRP composite. Therefore, the effect of fiber content on the mechanical properties of SFRP composites is of particular interest and significance. It is often observed that the increase in fiber content leads to the increase in the strength and modulus [6–12].

Mechanical properties of the composites obtained from plastics and fibers can vary depending on the fiber distribution in the structure, fiber size, fiber content and fiber–matrix adhesion force. In order to affect a high adhesion force between the matrix and fiber, fibers are coated with materials with less surface energy, like silane. By doing so, wettability of the matrix is improved [13–15].

Polyamides are commonly used in a wide range of engineering applications because of low cost, high yield, high molecular weight and crystallinity, and they possess excellent mechanical properties and processability [16–18]. The major deficiencies of polyamides for industrial applications are their high moisture absorption and high notch sensitive characteristics. These deficiencies can be improved by blending with other polymers or with the elastomers [20, 21]. Cast polyamide is a partially crystalline thermoplastic which is produced by means of anionic polymerization of ε-caprolactam [19,22]. In a pressureless casting process, the liquid monomer is polymerized via a controlled chemical reaction directly to a semifinished product. Cast polyamide also known as castamide or PA 6 G has got many advantages over other polymer and metal materials. PA 6 G is the classical slider material for highly loaded machine components such as bearings, bushes, slider pads, guide pads, as well as gears and sprockets. It shows high wear resistance at low and medium speeds in particular under harsh conditions, e.g., dust or sand contamination in the bearings. Good damping properties for the reduction in vibration and noise, particularly in the case of wire rope and conveyor rollers, are of particular interest. PA 6 G reduces vibration which is transferred from metallic rollers to shafts, bearings and machine frames [23,24]. Low specific weight reduces component weight compared to that of metallic materials. This is of particular interest where parts rotate and centrifugal force is generated. This is considerably reduced due to the lower weight and also reduces the associated unbalances and vibrations. Good machining, dimensional stability, low residual stresses allow production of complex engineered components and application in all design areas. There is a very strong relationship between tribological and mechanical properties of materials. Therefore, the researchers added various fillers to improve friction and wear behavior of the composites with increasing mechanical properties, such as graphene, boron nitride, carbon black and fibers. Recently, a considerable amount of the literature has been published on cast polyamide-based composite materials. However, in all of these studies, the reinforcing materials and fillers were introduced to the polymer matrix at the polymerization stage. In reviewing the literature, no study was found on the added materials after polymerization process. Thus, in the present study, E-glass fiber was added to the polymer matrix as a reinforcing material after polymerization process, and the effect of the short-fiber content on the mechanical properties of cast polyamides was investigated.

2 Experimental

2.1 Materials and Methods

In this study, cast polyamide was used as matrix material obtained from Polikim firm [25] in Turkey. The properties of cast polyamide are given in Table 1.

Cast polyamide rod was cut by a sewing machine in order to get flake-type castamide chips in composite production. Short E-glass fiber used as reinforcing material was obtained from Cam Elyaf Company [26] in Turkey at the dimension of 13 µm diameter and 3 mm length. The fibers were in bunch form. The properties of the E-glass fiber are given in Table 2.

The composite materials were produced by injection molding method at the different fiber contents ranging vol-

Table 1 Properties of the cast polyamide

Property	Unit	Castamide
Density	gr/cm^3	1,10
Water absorption	%	7
Tensile strength	MPa	80
Modulus of elasticity	GPa	4
Tensile elongation	%	>20
Compression strength	Kg/cm^2	950
Compression modulus	MPa	2,700
Impact strength (Izod, notched)	kJ/m^2	5.6
Hardness (Shore D)	Shore D	84
Wear rate	mg/km	0,44
Melting temperature	°C	220
Coefficient of heat expansion	°C^{-1}	8×10^{-5}

Table 2 Properties of E-glass fiber

Property	Unit	E-glass fiber
Density	gr/cm^3	2.56
Tensile strength	MPa	3,445
Modulus of elasticity	GPa	76
Tensile elongation	%	2.75
Fiber diameter	µm	13
Chopped length	mm	3
Moisture content	%	maks. 0.1
Chemical composition	% (weight)	52.4 SiO_2
		14.4 Al_2O_3
		10.6 B_2O_3
		4.6 MgO
		17.2 CaO
		0.8 other

Table 3 Castamide and fiber contents of composite materials

Specimen code	E-glass fiber		Castamide	
	Weight ratio (%)	Volume ratio (%)	Weight ratio (%)	Volume ratio (%)
CA10	10	5.5	90	94.5
CA20	20	11.1	80	88.9
CA30	30	18.3	70	81.7
CA40	40	25.8	60	74.2
CA50	50	34.3	50	65.7
CA60	60	43.9	40	56.1
CA70	70	54.9	30	45.1

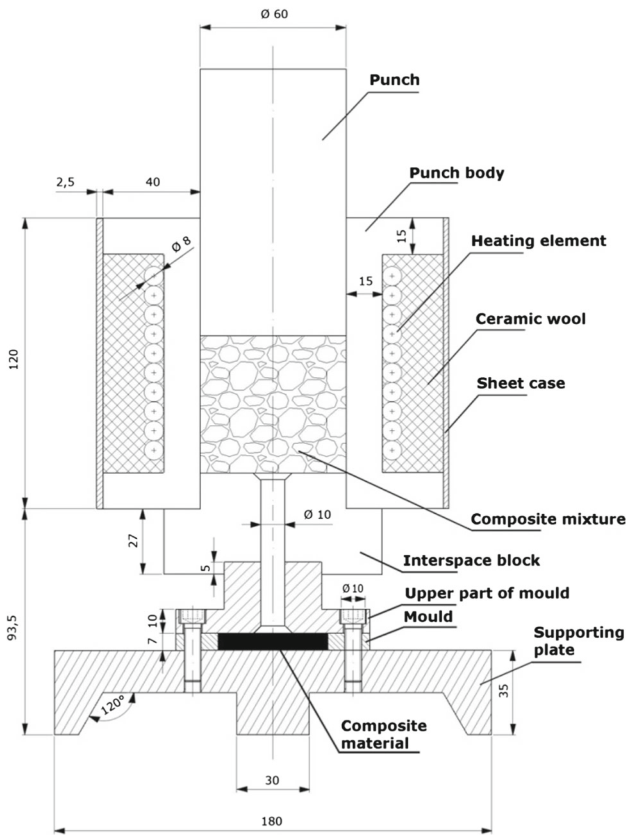

Fig. 1 Technical drawing of injection-type molding system used in composite production

ume ratio from 5.5 to 54.9 %. The volume and weight ratios of castamide and fiber used in composite materials are given in Table 3.

In order to produce castamide-based composite materials, a purpose-built injection-type molding system was designed and manufactured in the laboratory as shown in Fig. 1. System consists of a heating control system, mixing chamber, mold, punch, etc. Punch movement was managed via a hydraulic press having double strokes as downward and upward motion. For composite production, firstly the flakes of castamide and short glass fibers were weighed at a scale with an accuracy of 0.001 gr. The composite mixture at the different volume ratio of fiber and castamide was hand-mixed at the room temperature to obtain homogeneous mixture. After this process, the mixture was put into the composite chamber which was preheated to $280 \pm 1\,°C$ by a temperature controller unit. The composite mixture was held at this temperature for about 10 min, and then, the punch was removed from the chamber and the mixture was stirred at the molten state by using a mechanical mixer to get homogenous distribution of fibers in the castamide matrix. Then, the composite mixture was injected from composite chamber into the mold cavity by the punch movement and held in the cavity at a pressure of $7\,N/mm^2$ and at a $280 \pm 1\,°C$ temperature for 5 min. Later, the mold was left to cool at room temperature. The punch, punch body and the mold surfaces were sprayed by using a mold-releasing agent before production. In addition, an aluminum foil was placed on the punch and mold interfaces to prevent melt leakage. The solid composite material with the dimension of $120 \times 55 \times 7$ mm was removed from mold and cut by a saw to prepare test specimens such as tensile and impact tests according to ASTM standards.

2.2 Tests

Tensile tests were carried out on the tensile specimens prepared according to ASTM D 638-03 standard. The test was conducted at room temperature at a constant crosshead-speed of 5 mm/min with an Instron computer-controlled testing machine. At least three specimens were tested, and the average value was taken. At the end of the tests, tensile strength, modulus of elasticity and percent elongation of composites were determined.

Impact tests were carried out on the specimens having $10\times 50\times 7$ mm dimensions in a Charpy-type impact machine. The specimens were tested under unnotched condition at room temperature. At least three impact specimens were used in the tests, and the average value was taken for each composite. Impact strength of the composites was calculated as the ratio of fracture energy to the cross-sectional area of the specimen.

Density measurements were also done on the specimens which were produced from the composites. The mass of the specimens was weighed in a digital scale at an accuracy of 0.1 mg, and the volume of specimens was calculated by measuring the dimension of specimens ($7 \times 60 \times 7$ mm) at an accuracy of 1 μm. Then, the density was calculated using the formula as $\rho = m/V$, where m and V are mass and volume, respectively.

Fracture surfaces of the specimens obtained from impact tests were examined in a scanning electron microscopy (SEM Zeiss EVO LS 10). Before SEM examination, sample surfaces were gold-sputtered by a Emitech SC 7620 surface coating machine.

3 Results and Discussion

The castamide flakes were used in composite production as matrix materials. The flake size was observed at a different size in the range of 50–500 μm having irregular shape and edges. On the other hand, the E-glass fibers were used as reinforcing materials which is in the bunch form. However, this bunch form was splitted into single fibers during composite mixing.

The density and some mechanical properties of composite materials such as tensile strength, modulus of elasticity, impact strength and tensile elongation are given below in Table 4.

Figure 2 shows the effect of fiber volume content on the density of composite materials. It is apparently seen that the density of composites increases with the increase in fiber content. The density of composite was 1.15 g/cm^3 at the 5.5 % fiber volume ratio, whereas it reached the value of 1.73 g/cm^3 at the fiber volume content of 54.9 %. This increase was solely arisen from the increasing fiber content in the composites. E-glass fiber has got higher density (2.56 g/cm^3) than that of the castamide (1.10 g/cm^3) as shown in Tables 1 and 2.

The effect of fiber volume ratio on the tensile strength of composite materials was given in Fig. 3. As seen in the figure, the tensile strength increases with the increasing fiber content up to volume ratio of 34.3 %. The tensile strength

Table 4 Density and mechanical properties of composite materials

Specimen code	Property				
	Density (g/cm^3)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Tensile elongation (%)	Impact strength (J/cm^2)
CA10	1.15	82.0	4.5	4.2	5.24
CA20	1.19	88.1	5.5	3.5	4.57
CA30	1.24	97.6	6.8	2.6	4.06
CA40	1.30	117.2	8.0	1.9	3.68
CA50	1.37	125.7	9.5	1.3	3.25
CA60	1.54	100.4	8.1	1.1	2.21
CA70	1.73	84.4	7.5	1.05	2.42

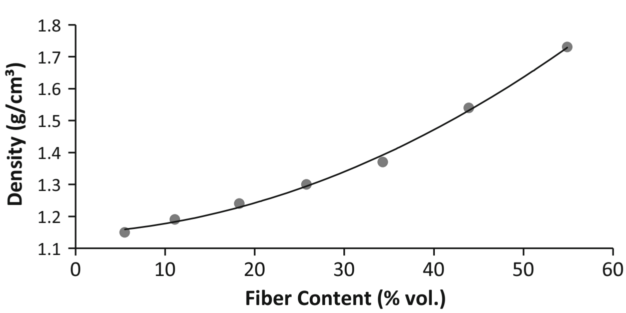

Fig. 2 Effect of fiber volume ratio on the density of composites

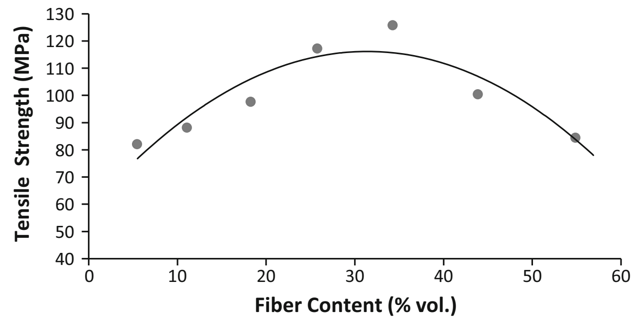

Fig. 3 Variation of tensile strength versus fiber volume ratio

of the composite was 82 MPa at the fiber volume ratio of 5.5 %, while it increases to 125 MPa at the fiber volume ratio of 34.3 %. The tensile strength of the composite decreases with the increasing fiber ratio, and it descends to 84 MPa at the fiber volume ratio of 54 %. It can be said that the fiber content in the composites makes positive effect on the tensile strength up to 34.3 % fiber volume ratio, whereas the fiber addition above this value makes adverse effect on the tensile strength of the composites. The percent improvement of fiber content on the tensile strength of composites was 65 % when compared to the ultimate strengths 82 and 125 MPa at the volume ratio of 5 and 34.3 %, respectively. Strength increment in polymers by the addition of short fibers is a well-known and the most-used method [27].

This study produced results which corroborate the findings of other studies. Gullu et al.'s [28] study demonstrates that fiber weight ratio and fiber length were the substantial effect on the increase in tensile strength of the polyamide 6-based composites. It was found that percent strength improvement on the composites was 74 and 111 % at the fiber weight ratio of 15 and 30 %, respectively.

The strength decreasing at the high fiber content (higher volume ratio of 34.4 %) can be explained by matrix wetting effect in which the fibers were homogeneously surrounded by matrix, but at high fiber content, it is difficult to surround all the fibers by matrix homogenously. Furthermore, fiber–matrix interface strength decreases with the increase in fiber content due to insufficient matrix materials. In Fig. 4, it can be seen that the fibers were not surrounded by polymer matrix, and they appeared as single fiber and bundle fiber form. They were not distributed homogeneously in matrix, and they were stayed in matrix as huge fiber bundle form.

The variation of the modulus of elasticity of composites versus fiber content was given in Fig. 5. This figure also shows identical behavior as it occurred in tensile strength graphs (Fig. 3). It was well known that modulus of elasticity increases with the increase in tensile strength or vice versa for composite materials [29]. Modulus of elasticity of composites increases with the increase in the fiber content up to 34.3 % in which it shows a peak value (9.5 MPa) and then it

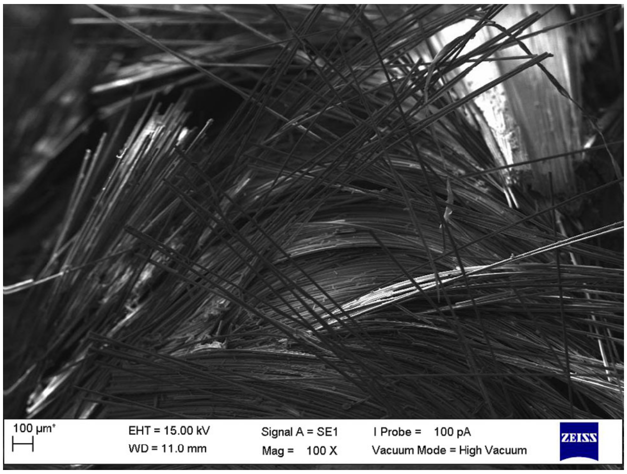

Fig. 4 Fracture surface appearance of the composite having fiber volume ratio of 34.4 %

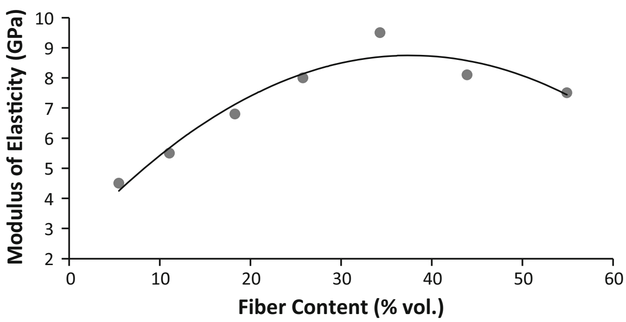

Fig. 5 Effect of fiber content on the modulus of elasticity of composites

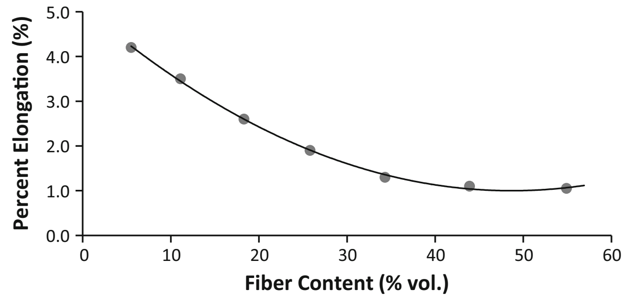

Fig. 6 Effect of fiber content on the percent elongation of composites

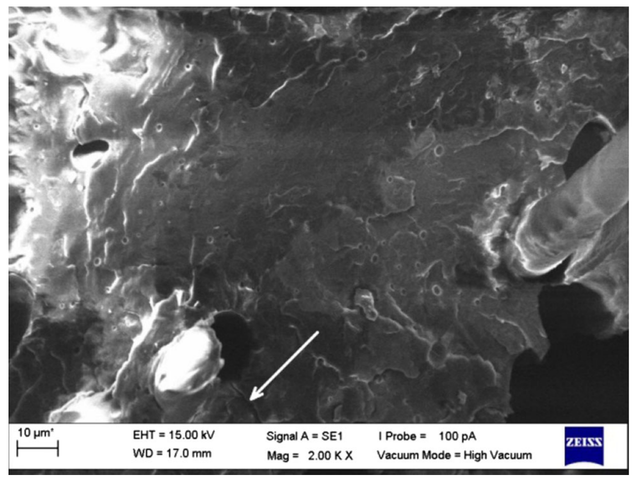

Fig. 7 Crack formation around of fiber

decreases with increasing fiber content. Modulus of elasticity shows low value at the low fiber content (5.5 %) as 4.5 GPa, while it reaches 9.5 GPa at the fiber volume ratio of 34.3 and then it decreases to the value of 7.5 GPa at the fiber volume content of 54.9. It was found that approximately 111 % increment in the modulus of elasticity was observed at the fiber volume ratio of 34.3 %, and similar results were found by Fu et al. [30]. They found that the addition of short glass fiber at the fiber volume fraction of 25 % into the polypropylene matrix was shown an increase of 100 % in elastic modulus of composites.

Figure 6 shows the variation of fiber content versus percent elongation in tensile testing. As seen in Fig. 6, the percent elongation of composites decreases with increasing fiber content. Percent elongation was 4.23 at the fiber volume ratio of 5.5, while it falls to 1.05 at the fiber volume ratio of 54.9. In other words, the composite materials came about brittle manner with the increase in fiber content in the composites. E-glass fiber is a ceramic-based fiber and shows low elongation such as 2.75 % (Table 2). It is well known that fiber addition reduces ductility values of polymer-based composites [27]. The reduction in the elongation is caused by an embrittlement effect as the UTS (ultimate tensile strength) of composites is improved (see Fig. 3) when the fiber volume content is increased. The cause of this effect has been identified as matrix crack formation at the ends of the reinforcing fibers. Subsequently, as the strain is increased, more cracks had formed progressively at the ends of shorter fibers. Initially, this cracking can be accommodated by load transfer to adjacent fibers which "bridge" the cracked region. Final failure occurs when the extent of cracking across the weakest section of a specimen reaches a critical level when the surrounding fibers and matrix can no longer support the increasing load. The findings of the current study are consistent with those of other studies by Fu et al. [30]. The matrix cracking at the fiber end was shown in Fig. 7 as indicated by an arrow. In addition to that, more fiber requires more matrix materials to surround the fibers. Figure 8 shows that insufficient matrix material and non-homogenous fiber distribution may lead to low modulus of elasticity at high fiber content such as beyond 34.4 %.

They were shown that percent elongation decreased to the 1.2 from 2.2 % with increasing the fiber volume fraction from 8 to 24 % [28]. On the other hand, it was shown by researchers that the addition of fiber from 0 to 30 % into polyamide (nylon), the percent elongation was decreased from 50 to 2 % [27]. In addition, as the fiber content increased, the matrix

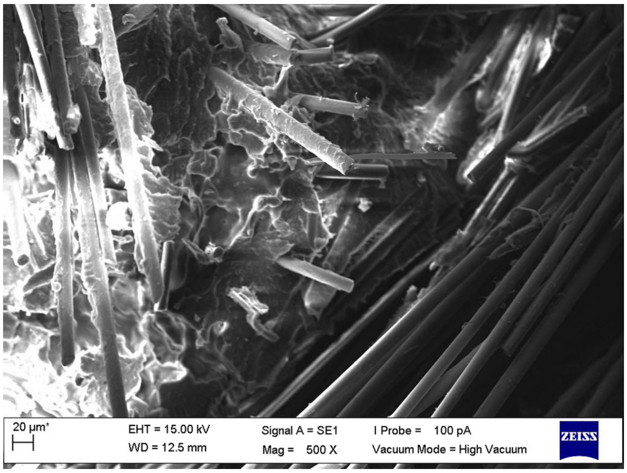

Fig. 8 Non-homogenous fiber distribution at high fiber content 34.4 %

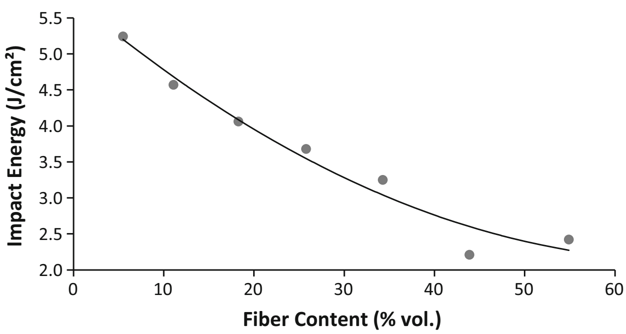

Fig. 9 Effect of fiber content on the impact strength of composites

was insufficient to wet the fiber entirely and led to poor interfacial bonding between the fiber and the matrix. When force is applied, the composite has tendency to fail rather to elongate.

The variation of impact energy of composites versus fiber volume content was given in Fig. 9. All samples broke through completely, producing two separate pieces with fractured free ends, and it showed brittle fracture signs such as no substantial plastic deformation. From Fig. 9, it can be clearly seen that the impact strength of composites decreases continuously with the increasing fiber content up to percent volume ratio of 54.9 %. The impact energy of composite was 5.24 J/m^2 at the fiber content of 5.5 %, while it showed a low value as 2.42 at the fiber content of 54.9 %. Impact energy decrement especially at high fiber content was due to brittle behavior of composites. The impact and tensile elongation curves showed similar trend such that the data in both curves were decreased while the fiber content increased. Low and high fiber content fracture surfaces were given in Fig. 10a, b, respectively.

The tensile strength (σ_c) of SFRP composites can be predicted using the modified rule of mixtures equation [31]:

$$\sigma_c = \lambda_\sigma \sigma_f V_f + \sigma_m (1 - V_f) \quad (1)$$

where λ_σ is the fiber efficiency factor for the composite strength. V_f is the fiber volume fraction. σ_f and σ_m are the tensile stress of fiber and matrix, respectively.

Similarly, the tensile modulus of elasticity (E_c) of SFRP composites can be predicted using the modified rule of mixtures equation:

$$E_c = \lambda_E E_f V_f + E_m (1 - V_f) \quad (2)$$

where λ_E is the fiber efficiency factor for the composite modulus considering the effects of fiber length and orientation. E_f and E_m are the elasticity modulus of fiber and matrix, respectively.

Fiber efficiency factor variations versus fiber volume fraction were given in Fig. 11a, b for tensile strength and modulus of elasticity, respectively. As seen from the figures, both fiber efficiency factors increase with increasing fiber volume fraction. After exhibiting a peak value, they are decreasing with increasing fiber volume fraction. These figures show similar behavior of tensile strength and modulus of elasticity curves given in Figs. 3 and 5, respectively.

It can be seen that the fiber efficiency factor λ_σ for the strength is much lower than the fiber efficiency factor λ_E for the modulus of elasticity. This situation can be explained by mean and critical fiber lengths. It was reported that [28] the fiber efficiency factor λ_σ for the strength is dependent on both mean fiber length and critical fiber length, while the mean fiber length may be much lower than the critical length; thus, this leads to a relatively low fiber efficiency factor λ_σ for the strength. It was also reported that mean glass fiber length decreases with the increase in glass fiber volume fraction due to increased fiber–fiber interaction and fiber–equipment contact [28]. In the current work, the fiber was 3 mm length, but at the high fiber fraction, this value can decrease due to fiber–fiber and fiber–mixer interactions during mixing time.

On the other hand, the modulus is a property of material at low strain and is not very sensitive to the fiber–matrix interface or critical fiber length. Hence, the fiber efficiency factor λ_E for the modulus of elasticity is relatively high. Fiber efficiency factor results were found in good agreement with the study of Fu et al. [30]. Fiber efficiency factor in the modulus of composite was found as 0.25 at the fiber volume ratio of 30 % in the present study, whereas it was found as 0.4 at the fiber content of 24 % in short glass fiber-reinforced polypropylene composites by Fu et al. However, fiber efficiency factor for tensile strength was found as 0.065 at the fiber content of 25.8 % in the present study, whereas it was found as 0.08 at the fiber content of 25 % by Fue et al.

4 Conclusions

The following conclusions can be drawn under the light of above results:

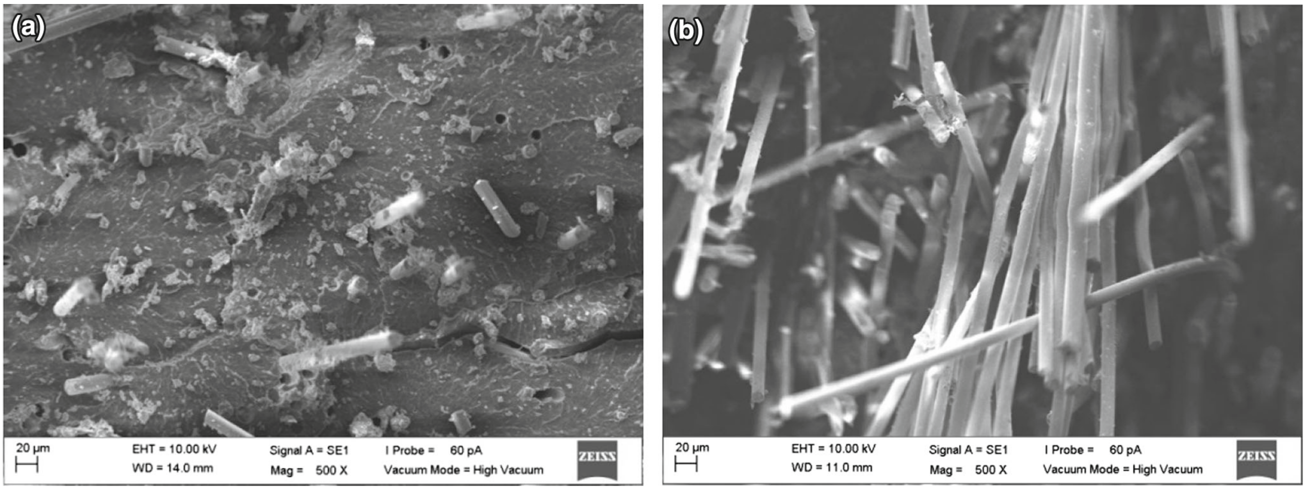

Fig. 10 Fracture surface appearance of composite having fiber volume ratio of **a** 11.4 % and **b** 34.4 %

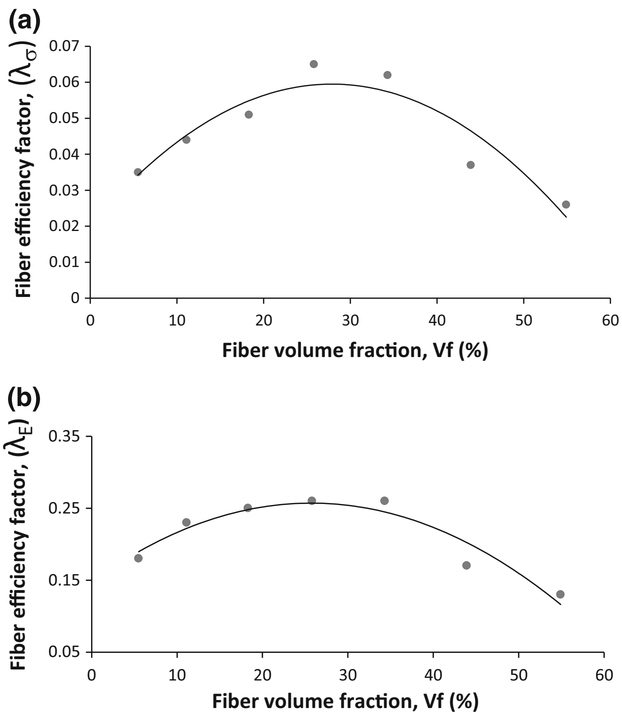

Fig. 11 **a** Fiber efficiency factor for the tensile strength and **b** modulus of elasticity of composites as a function of fiber volume fraction

1. The density of composites increased with increasing the fiber content up to 55 % volume ratio of fiber.
2. The mechanical properties of cast polyamide-based composites such as tensile strength and modulus of elasticity increased with increasing fiber content up to 35 % fiber ratio, and after this point, increasing fiber content inversely affected these properties.
3. The impact energy and tensile elongation of composites decreased with the increase in fiber content.
4. Fiber efficiency factors for tensile and modulus of elasticity increased up to 35 % fiber ratio, but above this value, it decreased with increasing fiber content
5. The fiber efficiency factor for modulus of elasticity was higher than that of tensile strength.

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