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Evaluation of morphological characteristics and mechanical performance of Rockforce mineral fiber- and glass fiber-reinforced polyamide-6 composites

Abstract: In this study, the effect of addition of Rockforce mineral and glass fiber fillers on the mechanical properties and morphological characteristics of polyamide-6 composites were evaluated and compared. Reinforcements, single and mixed compounds by various weight ratios between 10 and 30 wt%, were added to polyamide-6 polymer. Uniaxial tensile, Izod impact, and flexural tests were carried out. Tensile strength, elongation at break, tensile modulus, flexural strength, flexural modulus, and impact strength were obtained. The results showed that the tensile strength, tensile modulus, flexural strength, and flexural modulus of polyamide-6 composite increased with the increase in the glass fiber ratio and are slightly influenced by the addition of Rockforce mineral fibers. Moreover, the impact strength follows an increasing and decreasing profile, whereas elongation at break values decreased with the increase in reinforcement ratio. Finally, scanning electron microscopy was used for comparison and evaluation of the fracture surface of the polyamide-6 composite.

Keywords: composite; glass fiber; mechanical properties; Rockforce.

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1 Introduction

Viewing polymer materials from an engineering perspective, polyamide-6 (PA6) is one of the most widely used engineering thermoplastics because of its balanced combination of properties. Its stiffness, strength, heat resistance, and high degree of toughness make polyamides ideal materials for technical applications. Having said

that, polyamides achieve a high level of properties through a symbiosis with reinforcing agents such as glass fiber, glass beads, talc, mica, wollastonite, silica, and clays [1]. Blanchet and Kennedy [2] proposed that the filler materials embedded in the polyamide reduce the subsurface deformation and interrupt crack propagation. Furthermore, the addition of glass fibers obstructs the fragmentation of the PA6, resulting in the formation of small discontinuous fragments, which reduces the tribological and some mechanical properties of this material [3]. There are numerous research publications on the role of different types of fiber in polymer composite [4–6], but there is no announced research on polymer composite filled with Rockforce mineral fiber filler. However, there is a wide range of research in the role of filler in PA6 composite particularly involving glass fiber filler. The influence of glass fiber filler on the performance of PA6 polymer composite was investigated [7–10]. These studies showed the enhancement in stiffness and strength of PA6 with the presence of glass fiber filler. Unal et al. [11] studied the abrasive wear behavior of polymeric materials and concluded that the composites show inferior wear behavior than that of the parent polymer due to the reduction in the ultimate tensile strength and the elongation to break of the composite material. Unal et al. [12, 13] also studied the mechanical behavior of PA6 composites containing glass beads, talc, kaolin, and wollastonite. They concluded that the addition of these fillers to nylon 6 improves the tensile strength and elastic modulus but weakens the impact strength and the ductility of the polymer. Yoo et al. [14] investigated the morphological characteristics and mechanical properties of glass- and clay-reinforced nylon 6 composite. They concluded that the glass fibers are well dispersed in the matrix, which results in an increase in tensile strength and a decrease in elongation at break, while the impact strength increased with glass fiber content and decreased with clay content in the composite material. Arsad et al. [15] and Kannan and Misra [16] studied the mechanical and rheological properties of PA6/(ABS) acrylonitrile butadiene styrene blends with and without short glass fiber.

They found improved tensile strength, flexural strength, and low elongation that is attributed to the phase separation, resulting in less compatibility between PA6 and filler.

Rockforce mineral fiber is one of a set of products of rock wool produced by Lapinus; its stiffness, tensile strength, and elongation to break and impact are on a comparable level with that of glass fiber fillers. The addition of this mineral fiber to PA6 has the advantage of less machine wear; less increase in viscosity, shrinkage, and warpage; less burning rate; high surface quality; high dimensional stability; more flexibility of the compound and filling gaps on the price scale between glass fiber and low aspect ratio filler.

It is clear from the literature survey on PA6 composites that the glass fiber filler has been used as a filler but there is no investigation into using Rockforce mineral fillers. The main aims of this study are to evaluate the mechanical and morphological characteristics of Rockforce mineral fiber- and glass fiber filler-reinforced PA6 composites and to evaluate composite material costs. In view of this, composite compounds were prepared and faced mechanical tests and morphological examinations.

2 Experimental work

A commercially available PA6 engineering polymer (Domamid 27, Domopolymers, Belgium) with a density of 1.14 kg/m³ was selected as polymer matrix material. Two types of reinforcements were used and investigated: Rockforce mineral fibers (RF-MFR) and E-type short glass fiber (SGFR). Rockforce mineral fiber with an amino-silane surface treatment (Rockforce 825) was obtained from Lapinus Fibres in Holland and E-glass fibers were obtained from Gebze, Turkey. (For specifications and dimensions, see Tables 1 and 2.) Composites were prepared by injection molding as follows: Fibers were first

Table 1 Chemical composition of Rockforce mineral and E-glass fiber.

Constituent	Rockforce fiber (wt%)	E-glass fiber (wt%)
SiO ₂	38–43	50–56
Al ₂ O ₃	18–23	12–16
B ₂ O ₃	N.A.	5–13
TiO ₂	0.6–2.6	0–1.5
MgO+CaO	23–28	16–31
Na ₂ O+K ₂ O	<4.5	0.5–2.5
Fe ₂ O ₃	–	0–0.8
Fe	4.5–8.0	–

N.A., not applicable.

Table 2 Physical properties of Rockforce mineral fiber and short glass fibers.

Constituent	Rockforce fiber	Typical chopped glass fiber
Specific density (g/cm ³)	2.75	2.55
Fiber diameter (μm)	5.5	10.5
Fiber length (μm)	150–200	3000–4500
Specific surface area (m ² /g)	0.20	0.12
Melting point (°C)	>1000	>600

dried in an oven at 100°C for 4 h to expel moisture prior to compounding with PA6 polymer. The compounding of the PA6 and fiber reinforcements was performed by using an NR II-75-type twin-screw extruder (Japan) with temperature profile (Table 3). Composites were prepared with different weight ratio combinations varying between 10 and 30 wt% (Table 4). Tensile and Izod impact samples were prepared using an injection molding machine with a barrel temperature of 225–265°C. Tensile tests were carried out at 50 mm/min crosshead speed using a universal testing machine (Zwick Z020, Switzerland). The tensile strength, tensile modulus, and elongation at break were recorded. Three-point bending tests were resumed using a Testometric Micro 350 (England) tensile test machine to obtain the flexural strength and flexural modulus of the composite materials. For impact tests, notches of 2.5-mm depth, angle 45°, and 0.25-mm radius were cut into the specimen using a motorized notch cutter. The Izod impact strengths of PA6 composites were determined by impact fracturing on a falling hammer type Zwick impact tester (Switzerland). To minimize error, all tests were repeated at least three times and the average values were plotted and reported. Finally, the morphology of the tensile fracture specimens was

Table 3 Injection molding process parameters for Rockforce mineral fiber- and short glass fiber-reinforced PA6 composites.

Injection molding process parameters	PA6+SGFR	PA6+RF-MFR
Feeding zone temperature (°C)	225	220
Precompression zone temperature (°C)	245	240
Compression zone temperature (°C)	255	245
Mold temperature (°C)	50	50
Injection speed (mm/s)	5.9	5.9
Injection pressure (MPa)	100	100
Injection time (s)	6.0	6.0
Drying temperature (°C) and time (h)	80°C, 4 h	80°C, 4 h

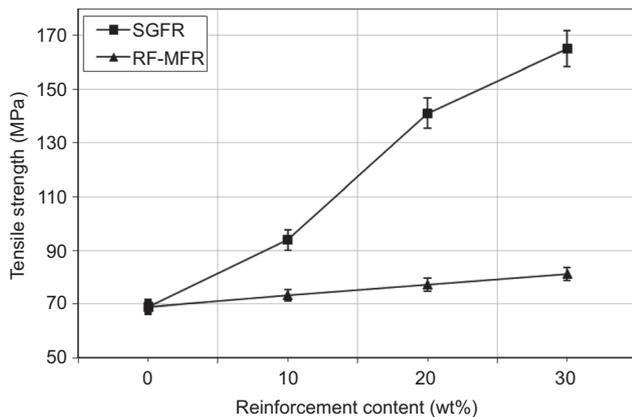
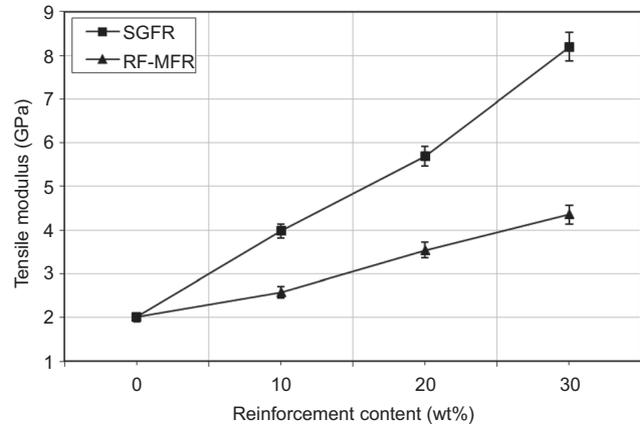
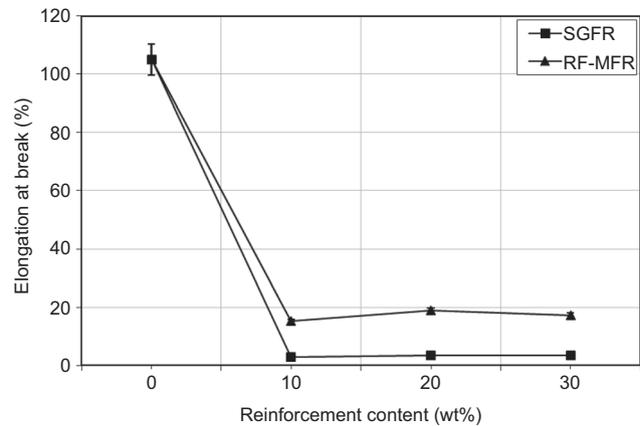
Table 4 Short glass fiber (SGFR)- and Rockforce (RF-MFR) mineral fiber-reinforced PA6 composite formulations.

Formulation	PA6 (wt%)	RF-MFR (wt%)	Short glass fiber reinforcement (wt%)
Neat PA6	100	0	0
PA6+10% RF-MFR	90	10	0
PA6+20% RF-MFR	80	20	0
PA6+30% RF-MFR	70	30	0
PA6+10% SGFR	90	0	10
PA6+20% SGFR	80	0	20
PA6+30% SGFR	70	0	30
PA6+10% RF-MFR+20% SGFR	70	10	20
PA6+20% RF-MFR+10% SGFR	70	20	10
PA6+30% RF-MFR+10% SGFR	60	30	10

evaluated by scanning electron microscopy. The accelerating voltage used was between 15 and 20 kV.

3 Results and discussion

Figures 1–3 present the variation in the values of tensile and flexural strength, tensile and flexural modulus, and elongation to break with Rockforce mineral and glass fiber filler content, respectively. It is clear from these figures and Table 5 that the tensile strength and tensile modulus increased with the increase in the short glass fiber reinforcement percentage. The increase in the tensile strength with 10, 20, and 30 wt% short glass fiber is about 28%, 100%, and 135%, respectively. The increase in Rockforce content percentage shows a small increase in tensile strength with 15% for 30% filler content. Figure 2 shows an increase in modulus of the composite with the increase of 10%, 20%, and 30% filler content. This increase is 100%,

**Figure 1** Variation of the tensile strength of PA6 with weight percent of reinforcement content.**Figure 2** Variation of the elasticity modulus of PA6 with weight percent of reinforcement content.**Figure 3** Variation of the elongation at break of PA6 with weight percent of reinforcement content.

175%, and 325% for SGFR and 25%, 75%, and 125% for the Rockforce mineral fillers. The increase in modulus of elasticity is explained by the percolation theory described by He and Jiang [17], which states that a matrix zone around each particle is affected by the stress concentration. Therefore, if the distance between particles is small enough, these zones join together and form a percolated network, which increases the modulus. Figure 3 shows that the elongation at break influences up to 10% filler content. There is a drop of 83% and 97% for SGFR and Rockforce, respectively. Above 10%, both fillers show insensitivity to filler content. This is explained by immobilization of the macromolecular chains by the reinforcement, which increases the brittleness of the polymer. Figures 4 and 5 display the variation of impact strength with filler content, and impact strength with tensile modulus of the composites. It is clear from these figures that the impact strength profile is following a decreasing and then an increasing

Table 5 Mechanical properties of neat PA6, single fiber-reinforced composite, and hybrid reinforcement composites.

Sample	Tensile strength (MPa)	Tensile modulus (MPa)	Elongation at break (%)	Flexural strength (MPa)	Flexural modulus (MPa)	Impact strength (kJ/m ²)
Unfilled PA6 (neat)	69±0.67	2012±28	105±0.81	93±2	1990±42	17.5±0.3
PA6+30% RF-MFR	81.22±0.5	4354±125	17.34±0.4	99.2±3	2679±59	12.2±0.5
PA6+30% SGFR	165±1.3	8196±66	3.58±0.22	193.7±1	5044±46	15.7±0.4
PA6+10% RF-MFR+20% SGFR	145±0.4	6118±51	3.61±0.26	124±4	3324±49	12.4±0.3
PA6+20% RF-MFR+10% SGFR	126±1.9	5840±67	4.28±0.44	111.7±4	3078±44	11.9±0.5
PA6+30% RF-MFR+10% SGFR	127±1.3	7016±56	3.47±0.55	108.5±3	3254±50	12.5±1.1

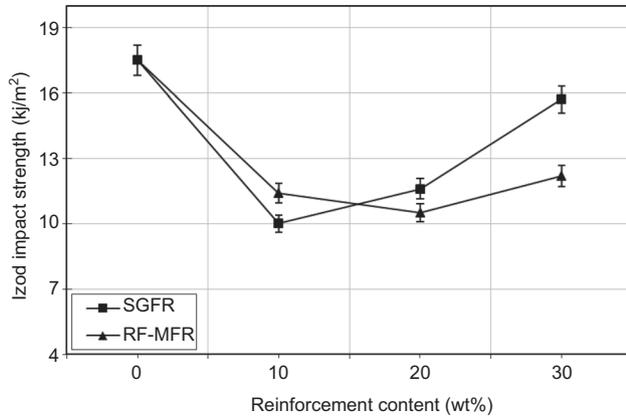


Figure 4 Variation of the impact strength of PA6 with weight percent of reinforcement content.

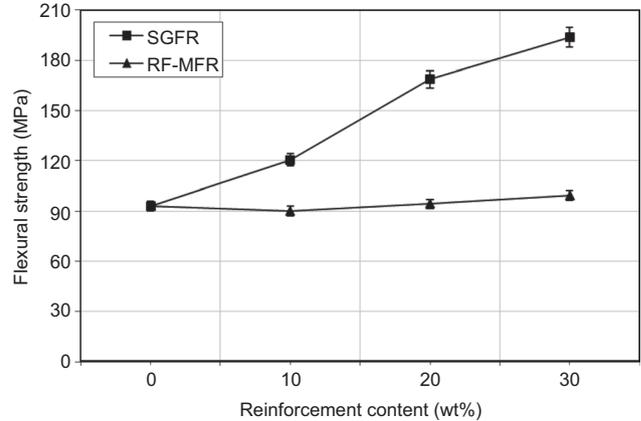


Figure 6 Variation of the flexural tensile strength of PA6 with weight percent of reinforcement content.

trend with increasing filler content. The decrease is about 80% and 60% for a 10% increase in filler content for SGFR and Rockforce mineral filler content, respectively. This suggests the lowest degradation in impact strength by the addition of mixed reinforcements. The impact strength decreases drastically with an increase in the filler content. This is mainly due to the reduction of elasticity of the material as a result of filler addition, thereby reducing

the deformability of the matrix and in turn the ductility in the skin area, so that the composite tends to form a weak structure. An increase in concentration of filler reduces the ability of the matrix to absorb energy and thereby reduces the toughness; thus, the impact energy decreases.

Figures 6 and 7 show the variation in flexural strength and flexural modulus with varying filler content. The flexural strength of composites increased with increase

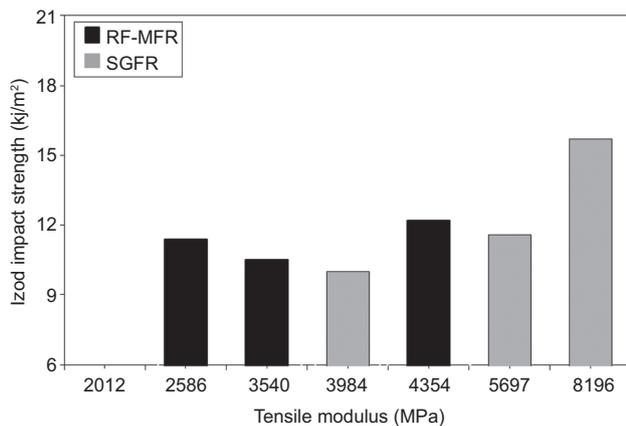


Figure 5 Variation of the notched Izod impact strength of PA6 with tensile modulus of composite.

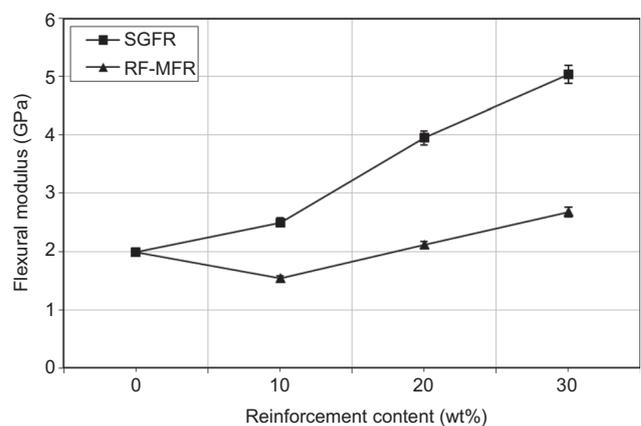


Figure 7 Variation of the flexural modulus of PA6 with weight percent of reinforcement content.

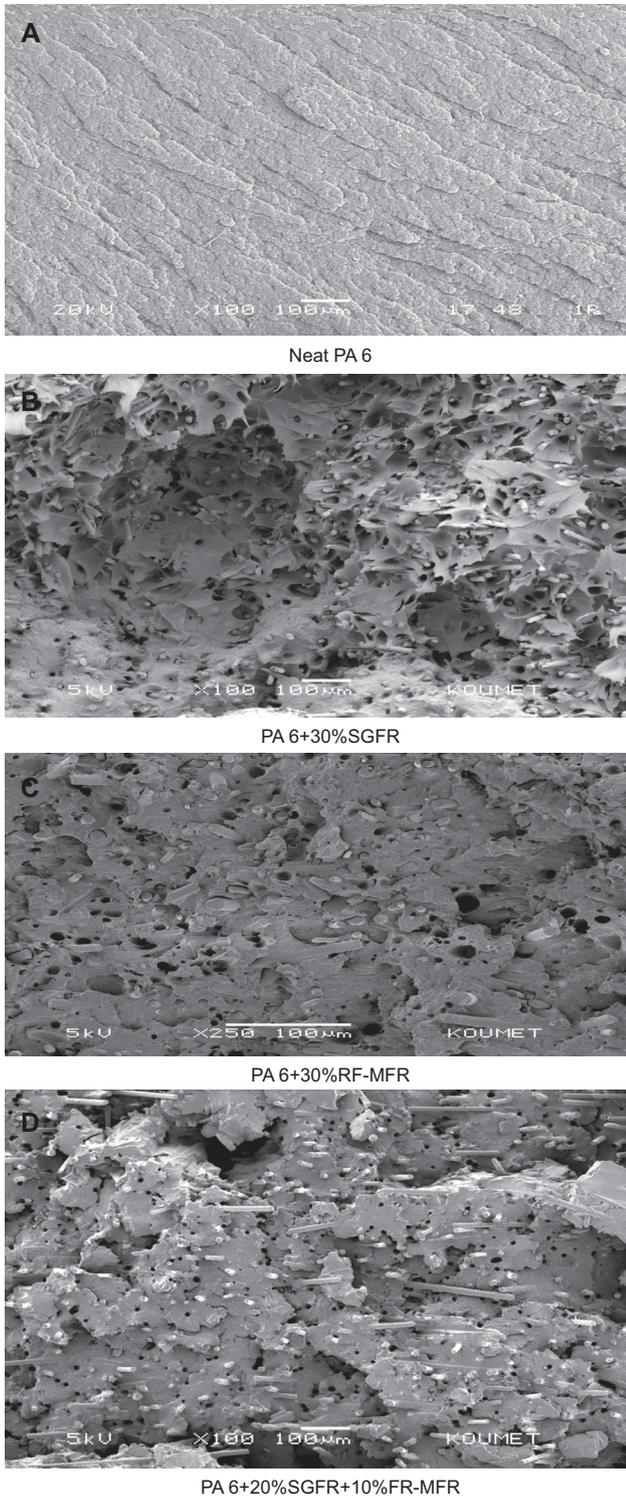


Figure 8 Scanning electron micrograph of tensile fracture cross section for PA6 with (A) neat PA6, (B) 30 wt% short glass fiber-reinforced PA6 composite, (C) 30 wt% RF-mineral fiber-reinforced PA6 composite, and (D) 20 wt% short glass fiber+10 wt% RF-mineral-fiber reinforced PA6 hybrid composite.

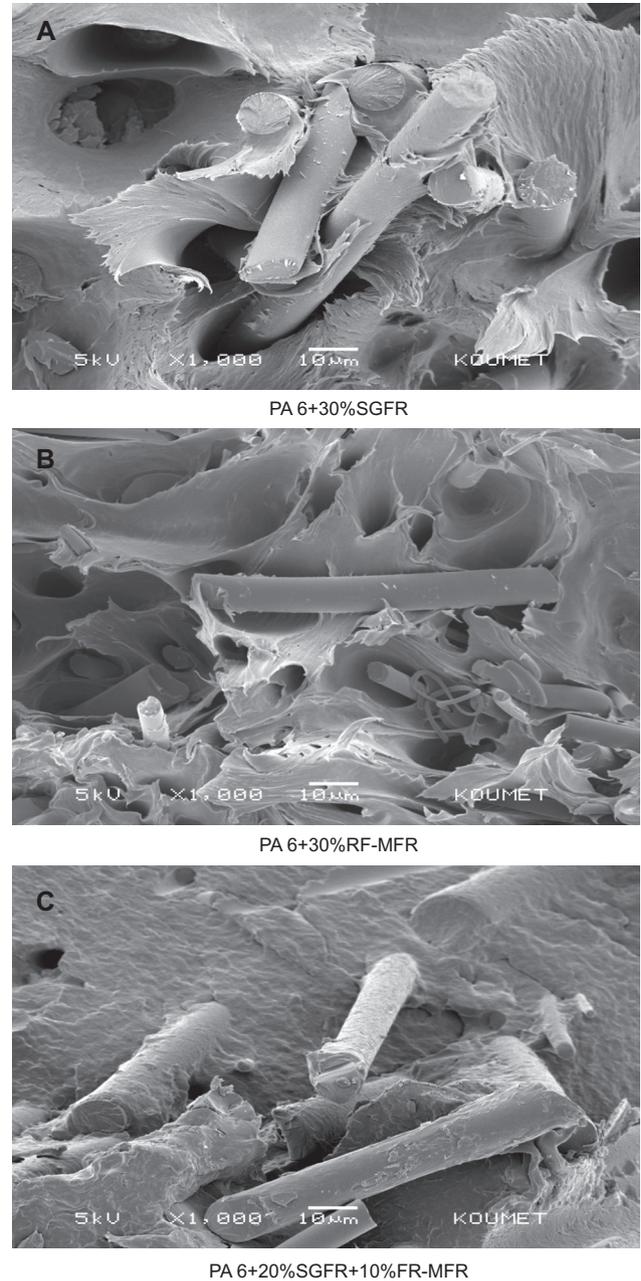


Figure 9 Scanning electron micrograph of tensile fracture cross section for PA6 with (A) 30 wt% short glass fiber-reinforced PA6 composite, (B) 30 wt% RF-mineral fiber-reinforced PA6 composite, and (C) 20 wt% short glass fiber+10 wt% RF-mineral fiber reinforced PA6 hybrid composite.

in filler content, and this increase is almost identical with the tensile strength and modulus values. It is worth pointing out that the total area of deformation stress has an important role in flexural properties. The flexural modulus increases with the increase in concentration of

glass fiber and Rockforce mineral filler content (Figure 7). Figure 8 presents the morphology of the fracture surfaces of tensile specimen composites and Figure 9 presents the higher magnification morphology pictures of (A) neat PA6, (B) 30 wt% short glass fiber-reinforced PA6 composite, (C) 30 wt% Rockforce mineral fiber-reinforced PA6 composite, and (D) 20 wt% short glass fiber+10 wt% Rockforce mineral fiber-reinforced PA6 hybrid composite. Figures 8B and 9A show well the embodiment and better interaction of glass fibers with the matrix material, whereas Figures 8C and Figure 9B show less interaction of rock force mineral fibers and the presence of undeformed Rockforce mineral fibers. This result explains the better mechanical properties of glass fiber PA6 composite than that of Rockforce mineral fiber-filled PA6 composite. Figures 8D and 9C show a good embodiment and interaction of the glass fiber with the matrix material for hybrid composites and also the presence of undeformed Rockforce mineral fibers. This explains the moderate mechanical properties of the hybrid composites. Therefore, to produce a sound PA6 composite with minimum cost, it is essential to use hybrid structure.

4 Conclusions

Rockforce mineral and E-glass fiber added to the PA6 polymer improved its rigidity and stability but dramatically decreased the impact strength and elongation

at break. The impact strength decreases at low filler content but improves at above 20% filler content due to the reduction of elasticity of the material thereby reducing the deformability of the matrix. With the addition of glass fiber only to the matrix material, the tensile and flexural strength increase. The most convenient single content of glass fiber in PA6 matrix material is at a 30 wt% ratio. The partial replacement of SGFR by Rockforce mineral filler increases the ductility and flexibility of the compound. Replacing 20% of glass fiber with rock force filler results in a high drop in material cost. Morphological studies showed that there is better interaction between E glass filler and the matrix at a high filler concentration. The best improvement in the properties of PA6 is reached with E-glass. The addition of rock force filler has the advantage of cheaper reinforcements, hence low overall cost.

Finally, for the reinforcement materials and with the weight ratios used in this investigation, the superposition of all the results indicates that apart from the elongation to break property, the addition of 30% glass fiber in a single ratio to PA6 is the most convenient filler ratio. From the point of view of strength, stability, flexibility and cost, the 10 wt% glass fiber+20 wt% Rockforce mineral filler combination is optimal.

Received June 18, 2013; accepted August 10, 2013; previously published online September 5, 2013

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