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Effect of polypropylene on the mechanical properties and water absorption of carbon-fiber-reinforced-polyamide-6/polypropylene composite

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ABSTRACT

Lightweight materials are becoming important in many industries, such as automotive, portable electronics, and so on. Polymer blends containing polyamide-6 (PA6) and polypropylene (PP) have been widely applied for weight reduction and low water absorption. It is well known that PA6 has a high affinity for water, and its mechanical properties and dimensional stability are often significantly affected by the absorption of water, whereas PP is characterized by its moisture resistance, low density and cost. The aim of our research was to investigate the effect of PP on the weight reduction, water absorption, dimensional stability and mechanical properties of carbon-fiber-reinforced PA6 composite in order to find a proper way to improve carbon-fiber-reinforced PA6 widely used in industry especially for high humidity or underwater applications. We assessed the mechanical properties by a tensile test and the microstructure by scanning electron microscopy for composites with and without water saturation. After being saturated with water, the composites with PP showed better ultimate tensile strength, elastic modulus, elongation, density for weight reduction and dimensional stability than the composite without PP.

1. Introduction

The reduction of weight is a primary method for increasing fuel efficiency and reducing emissions; for example, a 10% reduction in vehicle weight can improve fuel efficiency by 6–8% for conventional internal combustion engines or increase the range of a battery-electric vehicle by up to 10% [1,2].

One of the practical solutions in weight reduction strategies is the use of carbon fiber reinforced plastic instead of traditional materials. Compared to glass fibers, carbon fibers (CF) can lower the density and increase the strength and modulus, with excellent thermal and electrical conductivity, which makes them attractive for many applications, especially in the automotive industry [3]. Thermoset plastics are widely used as matrix materials. However, they cannot be melted and reshaped after curing, and recycling thermoset plastic is extremely difficult. On the other hand, thermoplastic matrix materials are convenient for recycling and mass production using injection molding, which allows designers to design the products they desire in terms of shape and structure. Thus, the use of carbon fiber reinforced thermoplastics (CFRTP) has attracted great interest among scientists because it enables significant reduction in the weight of parts while maintaining a high rigidity [4,5]. Moreover, CFRTP can be recycled by melting the material and reforming it into a new part. Among thermoplastic polymers, PA6 shows a strong matrix because of its good overall mechanical properties. However, PA6 is sensitive to moisture from the surrounding environment, and it can absorb water easily, even at room temperature. Its mechanical properties and dimensional stability are significantly affected by the absorption of water. Some researchers have found that the tensile strength of PA6 composites decreases significantly after storage in water compared to dry storage [6,7].

To reduce water absorption, PA6 is frequently blended with PP, which provides good resistance against moisture and ensures good processability [8]. Additionally, PP is a low-cost, low-density polymer, thus adding PP to PA6 composites reduces both the material cost and the density. Unfortunately, the polymers are incompatible because of their different polarities and crystalline morphologies. Enhancing the miscibility of the blend requires the use of a compatibilizer [9,10]. One widely used compatibilizer is maleic anhydride-grafted polypropylene (MAPP). In addition to its moisture resistance, PP is characterized by its low strength [11–13]. The literature lacks an evaluation of the influence of PP

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on the weight reduction, mechanical properties, water absorption and dimensional stability of PA6 composites in humid conditions, such as automotive exterior parts in the rainy season or underwater applications.

For this research, we prepared PA6/CF and PA6/PP/MAPP/CF composites by extrusion compounding and injection molding. We changed the PP ratio in the PA6/PP/MAPP/CF composites to evaluate the effect of PP composition on the mechanical properties, density, and water absorption. The ratio of PP/MAPP was constant in all cases. We compared the tensile test results and densities with PA6/CF (80/20 wt%) composites as a reference with and without water absorption. And finally a proper PP composition was proposed to improve carbon-fiber-reinforced PA6 widely used in industry especially for high humidity or underwater applications.

2. Experimental

2.1. Materials

The materials used in this research were commercially available products: polyamide-6 pellets (KN111, Kolon Plastic, Korea), polypropylene pellets (SI–170, Lotte Chemical, Korea), maleic anhydride-grafted polypropylene pellets (G-3003, Eastman Korea, Korea), and carbon fiber (CFU 6m, Napson Korea, Korea).

2.2. Sample preparation

All materials were preliminarily dried in an oven at 80 °C for 2 h and mixed together according to the ratios shown in Table 1 by a ball mill machine at room temperature. Then, we fed them into a single screw extruder through a feeding unit. We operated the extruder at a screw speed of 300 rpm and set the temperatures in the heating zones to 180–250–250–230–230 °C. The composites were extruded and cooled at room temperature. After that, we used a cutting machine to fabricate pellets with a length and radius of 5 mm and 3 mm, respectively. Before injection molding, we put the pellets into the ball mill again for 10 min to ensure uniform dispersion. The feeding zone of the injection molding machine was heated to 260 °C, and the melting zones and the nozzle were kept at 275 °C and 285 °C, respectively. We heated the mold to a temperature of 80 °C to reduce the cooling speed and ensure a more homogeneous crystallization [14]. The specimens used for the tensile and water absorption tests were molded in accordance with ASTM D-638.

2.3. Density measurement

In this experiment, the density of each specimen directly related to the weight reduction of the materials, as defined by the following equation:

$$\text{Density} = \text{mass}/\text{volume} \tag{1}$$

We obtained mass measurements for specimens using an electronic balance and calculated the volume by measuring the dimensions of the specimens. The densities used for each composite were the average value of three specimens.

Table 1
Composition of the composites.

No.	Name of composite	Composition	Mixing ratio (wt%)
1	0%PP	PA6/CF	80/20 (100%PA6, 0%PP)
2	10%PP	PA6/PP/MAPP/CF	71.74/7.96/0.5/20 (90%PA6, 10%PP)
3	20%PP	PA6/PP/MAPP/CF	63.37/15.84/1/20 (80%PA6, 20%PP)
4	30%PP	PA6/PP/MAPP/CF	55.17/23.65/1.5/20 (70%PA6, 30%PP)

2.4. Water absorption tests

Three specimens of each composite were immersed in distilled water at 23 °C (room temperature) in a temperature-controlled digital water bath (WB20, PolyScience, USA). We measured the weights of the specimens periodically, after removing the water on the surfaces, using a precision balance (AS60/220.R, RADWAG WaglElektroniczne, Poland) and repeated the procedure until the specimens were saturated. After the amount of water absorption reached its maximum value, the tensile tests were carried out. The amount of absorbed water was determined using the following equation:

$$M_t = \left[\frac{W_t - W_0}{W_0}\right] \times 100 \tag{2}$$

where M_t is the percentage water content, and W_t and W_0 are the instantaneous and initial weights of the sample, respectively.

In order to evaluate the dimensional stability after water absorption, the thicknesses of each specimen before water immersion and after saturated water were measured by the micrometer with a precision of 0.01 mm. The thickness of each specimen was measured three times with different positions. The thickness swelling (TS) was calculated according to the Eq. (3) [15]:

$$\text{TS}\ (\%) = \left[\frac{T_W - T_0}{T_0}\right] \times 100 \tag{3}$$

where T_0 and T_w are the thicknesses of the specimen before and after immersion, respectively.

2.5. Mechanical testing

The tensile tests were conducted using a universal tensile machine (Daek Yung Tech & Testers, Korea) at a constant crossspeed of 5 mm/min with a 50 mm gauge length of the extensometer, according to ASTM D-638. Accurate strain measurements were acquired using a laser extensometer. Tensile tests were performed with three specimens for each composite under two conditions: no water absorption (dry specimens) and saturated water absorption (wet specimens). The average results for each composite were reported. The Young's moduli were calculated as the gradient of the stress vs. strain curve in a strain range of 0.02–0.04% and analyzed the fracture surfaces using scanning electron microscopy (SEM).

3. Results and discussion

3.1. Weight reduction

As shown in Table 2, the reduction in density observed in the PA6/PP/MAPP/CF composites can be attributed to the lower density of PP in the composite matrix. The PA6/CF composite had the highest density at 1.14 g/cm^3. In the composite with 30 wt% of PP, the density decreased by 7.41% compared to the PA6/CF composite. This result shows that weight reduction accrues as the amount of PP in a PA6/CF composite increases.

Table 2
The density and percentage of density reduction compared with 0%PP.

No.	Name of composite	Density (g/cm^3)	Ratio of density reduction
1	0%PP	1.14	Reference
2	10%PP	1.11	2.63%
3	20%PP	1.08	5.41%
4	30%PP	1.06	7.41%