Study on the Effect of Carbon Fiber Addition on the Properties of Rice Straw-Plastic Composites

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Short carbon fiber (SCF), rice straw powder, and high-density polyethylene (HDPE) were melted, mixed, and compounded into composites by compression molding. The effects of carbon fiber content on the mechanical properties of rice straw-high density polyethylene composites (RHCs) were studied. The carbon fibers were characterized by a universal capability test machine (UCTM), scanning electron microscope (SEM), DMA dynamic mechanical analyzer, and a Fourier infrared spectrometer. The results showed that the addition of carbon fiber was beneficial to reduce the creep of RHCs. Meanwhile, the carbon fibers were broken after strength testing. The functional group types of rice straw WPC composites did not change, and the skeleton structure of WPC materials was still retained. When the content of carbon fibers was 9%, a large number of carbon fibers were surrounded by the HDPE matrix; the fibers were broken and rarely pulled out. The results showed that good interfacial bonding took place between the carbon fibers and the composites. The maximum tensile strength of the RHC/S9 was 15.15 MPa, which was 20.7% higher than that of default RHC, and the modulus of elasticity was 52.5% higher than that of default RHC. However, due to the large content of carbon fiber, the distribution of the carbon fibers was uneven in the matrix, and the toughness was reduced.

Keywords: Rice straw; Wood plastic composites; Carbon fiber; Elastic properties

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INTRODUCTION

Wood-plastic composite (WPC) is a new kind of composite material with the advantages of corrosion resistance, dimensional stability, high strength, and so on (Dang *et al.* 2017). It is made by crushing waste wood and crop straw, mixing them with thermoplastics (PE, PP, PVC, PS, *etc*.), adding various additives, and then hot-pressing, compounding, or melt extrusion (Jumadi *et al*. 2018; Zhang *et al*. 2018). WPC has the characteristics of both plastics and wood fibers, and their comprehensive properties are excellent. They are widely used in construction, packaging, automobile, decoration, gardening, *etc*. (Albano *et al.* 2001; Markarian 2005; Panthapulakkal and Sain 2006; Liu *et al.* 2009).

Simply improving the mechanical strength of straw-plastic composites by interfacial modification cannot meet the demand for these composites, and some modifiers come with high cost. Improving the mechanical properties of straw-plastic composites with reinforcing fibers is proposed to be a good way to expand their applications. Many studies have shown that reinforcing fibers can effectively improve the mechanical properties of straw-plastic composites. Ting *et al.* (2010) used the melt mixing and molding method to make polypropylene-based wood plastic composites, which was also composited with sisal fiber (SF) and glass fiber (GF). The impact strength, flexural strength, and flexural modulus of the composites were improved to varying degrees. Jarukumjorn *et al.* (2008) reinforced sisal fiber/polypropylene composites with fiberglass. The results showed that the addition of glass fiber improves the tensile strength, flexural strength, impact resistance, heat resistance, and water resistance of the composites. Guan *et al.* (2011) showed that basalt fibers significantly improve the flexural strength, impact strength, and tensile strength of wood fibers/polymers. Cui *et al.* (2006) used L-shaped glass fiber (GF) with a larger length and diameter to reinforce WPC. The flexural strength, flexural modulus, and impact strength of the composites were improved compared with composites made of ordinary WPC.

Carbon fibers are lightweight, good-sized, high in tensile strength, and have the characteristics of common carbon materials, such as high temperature resistance, friction resistance, electrical conductivity, thermal conductivity, and small expansion coefficient (Chen *et al.* 2018; Dang *et al*. 2018). Carbon fiber composites are commonly prepared by mixing carbon fiber with resin, metal, ceramic, or another matrix composite. These resulting composites maintain some excellent properties of carbon fibers and have a wide utilization in modern industry (Li *et al.* 2005). Among these carbon fibers reinforced composites, thermoplastics or thermosetting resins are mostly applied as the matrix to obtain high-performance carbon fiber reinforced composites due to the good interfacial compatibility (Quan *et al.* 2020; Huang *et al.* 2020). To expand the utilization of carbon fiber in sustainable materials, many researchers have focused on the carbon fiber reinforced wood-based composites. Dang *et al.* (2018) pointed out that the incorporation of carbon fiber would obviously increase the modulus of rupture and modulus of elasticity of polyethylene/wood fiber composites, with an increase of 38% and 96%, respectively. Zhang *et al.* (2019) prepared wood-flour/HDPE composites with continuous carbon fiber and found that carbon fiber made a large contribution to the increase in mechanical strength and toughness in comparison with glass fiber. Auriga *et al.* (2020) applied carbon fibers as a reinforcement layer between wood veneers and melamine-urea–formaldehyde resin. The cutting force showed better results for composite panels with carbon fiber in a perpendicular orientation. However, few studies on carbon fiber reinforced straw-plastic composites have been reported (Li *et al.* 2005; Ayrilmis and Kaymakci 2013; Du *et al.* 2015; Hao *et al.* 2018)

High density polyethylene (HDPE), as a thermoplastic material, has unique properties, such as excellent mechanical properties, good melt rheology, and it is commonly used plastic matrix in WPCs (Sun *et al*. 2019). Herein, HDPE was utilized to prepare the rice straw-high density polyethylene composites (RHCs), and the effects of carbon fiber content on the mechanical properties of resulting RHCs were investigated.

EXPERIMENTAL

Materials

Rice straw was taken from Suqian, Jiangsu Province, China, with a moisture content of 8.1%. The rice straw powder was obtained by grinding the rice straw in a micro plant mill and screening it to pass 40 mesh and be retained on 80 mesh screens. The rice straw powder was dried to a moisture content of 2.0% at 103 °C and stored in a dryer. High density polyethylene (HDPE) was provided by Sinopec Yangzi Petrochemical Co., Ltd.

(Nanjing Jiangsu Province China). The product model was HDPE 5000S, with a density 0.95 g/cm^3, and a melting index (MFI) 0.062 g/min to 0.13 g/min (190 °C). Its appearance was white and granular. It was crushed to pass through a 150 µm screen and dried to about 2% moisture content at 103 °C and stored in a dryer. Carbon fiber with a length of 3 mm was supplied by Ze Yu Sen carbon fiber products Co., Ltd. (Nanjing Jiangsu Province, China).

Table 1. Distribution Ratio of Carbon Fiber/Rice Straw-Plastic Composites

Sample Code	HDPE (%)	Rice Straw (%)	SCF (%)	Total Mass (g)	HDPE (g)	Rice Straw (g)	SCF (g)
RHC	70	30	0	220	154	66	0
RHC/S3	67	30	3	220	147.4	66	6.6
RHC/S6	64	30	6	220	140.8	66	13.2
RHC/S9	61	30	9	220	134.2	66	19.8
RHC/S12	58	30	12	220	127.6	66	26.4
Total mass	-	-	-	1100	704	330	66
Note: Solid Content, Oven Dry							

Methods

Preparation of carbon fiber/rice straw-plastic composites

A certain amount of carbon fibers was weighed and added into HDPE powder. The mixture of rice straw powder and HDPE/carbon fibers was pre-mixed evenly in the tray and then placed on a precision mill (Dongguan Zhenggong Mechanical and Electrical Equipment Technology Co., Ltd., ZG-160, Dongguan City, Guangdong Province, China). The blending time was 8 min. After mixing, the mixture was moulded. The conditions of the pressing process were as follows: temperature, 175 °C; pressure, 50 bar; and process time, 3 min. The sample needed for the flame retardant performance test was prepared in this way (Hao *et al.* 2018). The proportioning of carbon fiber/ *rice straw-plastic composites* is shown in Table 1.

Mechanical properties of carbon fiber/rice straw-plastic composites

Using the conditions set by GB/T13022 (1991), the test to determine tensile strength, was carried out on a computer-controlled electromechanical testing machine (Shenzhen New Sansi Material Testing Company, Shenzen, China). The dimensions of the sample were 100 mm (long)× 10 mm (wide)× 4 mm (thick); the loading speed was 1 mm/min. Continuous loading took place until the failure of the sample; this was repeated six times, and the average value was taken. Using the conditions set by GB/T9341 (2008), impact performance was tested on a pointer-type plastic pendulum impact testing machine (ZBC1251-1, Shenzhen New Sansi Material Testing Company, Shenzen, China). The dimensions of the sample were 80 mm (long) ×10 mm (wide) ×4 mm (thick). Continuous loading to failure was repeated six times and the average value was taken. Bending performance was tested in a computer-controlled electromechanical testing machine (CMT-4204, Shenzhen Xinsansi Material Testing Company, Shenzen, China). The dimensions of the sample were 80 mm (long) × 10 mm (wide) × 4 mm (thick). Continuous loading to failure was repeat 6 times, and the average value was taken (GB/T1451 2005).

Scanning electron microscopy test of carbon fiber/rice straw-plastic composites

Scanning electron microscopy (SEM, JSM-7600F, Japan Electronics Co., Ltd) was used to observe the surface morphology of rice straw-plastic composites modified by carbon fibers. Before the test, the samples were ground and sifted, and the powder of 200 µm to 450 µm in size was vacuum dried and sprayed with gold. The sample was observed under the acceleration voltage of 10 kV.

Creep (DMA) test of carbon fiber/rice straw-plastic composites

Creep resistance of carbon fiber/rice-straw wood-plastic composites was measured using a DMA dynamic mechanical analyzer (Q800, TA Instruments, USA) in a three-point bending mode. The test temperature was 0 to 1000 °C, the test stress was 5 MPa, and the test time was 30 min. Sample size: 60 mm (length) × 10 mm (width) × 4 mm (thickness).

FTIR test of carbon fiber/rice straw-plastic composites

An FTIR spectrometer (VERTEX 80V, Burker, Germany) was used to evaluate the functional groups of carbon fiber/rice straw-plastic composites. The surface of the composite was analyzed by attenuation total reflection infrared spectroscopy (FTIR), with a determination range of 4000 to 400 cm^{-1} and a resolution of 4 cm^{-1}.

RESULTS AND DISCUSSION

Mechanical Properties of Carbon Fiber/Rice Straw-Plastic Composites

The mechanical performance of rice straw-plastic composites with and without carbon fiber reinforcement are exhibited in Fig. 1 and Table 2. With the incorporation of rice straw powder, both the tensile strength, impact strength, and bending strength of RHC had an obvious decrease, compared with those of HDPE by itself. Interestingly, the addition of carbon fibers showed a positive effect on both the bending strength and the tensile strength of the resulting composites. When the carbon fiber content was 9%, the flexural strength of the composites increased by 26.5% compared with the default RHC. The flexural modulus increased by 7.7%, but not significantly.

Rice straw powder, as the reinforcing filler, strengthened the elastic modulus of HDPE, as shown in Fig. 1. Meanwhile, the elastic modulus increased gradually with the increase of carbon fiber mass fraction from 3% to 9%. When the content of carbon fiber was 9%, the elastic modulus increased by 52.5% compared with default RHC. The results showed that the elasticity and deformation resistance of carbon fiber/rice straw-plastic composites increased with the increase of carbon fiber.

Impact strength can characterize the toughness of the material. When the carbon fiber content was 3%, the impact strength of RHC/S3 composite was 32% higher than that of default RHC. This showed that the addition of carbon fiber improved the brittleness of RHCs. When the amount of carbon fiber was too high, agglomeration was more likely to occur in the extrusion process, and the dispersion uniformity decreased. When subjected to external impacts, the agglomerated parts that lacked resin penetration were prone to fracture, so when the carbon fiber content was 9%, the toughening effect was not significantly improved (Du *et al.* 2015). Although rice straw is not as strong as wood fiber, comparing with the impact strength of other wood-plastic composites (Vedrtnam *et al.* 2019), carbon fiber/rice straw-plastic composites became even tougher, which might be due to the good compatibility between carbon fiber and polymer matrix.

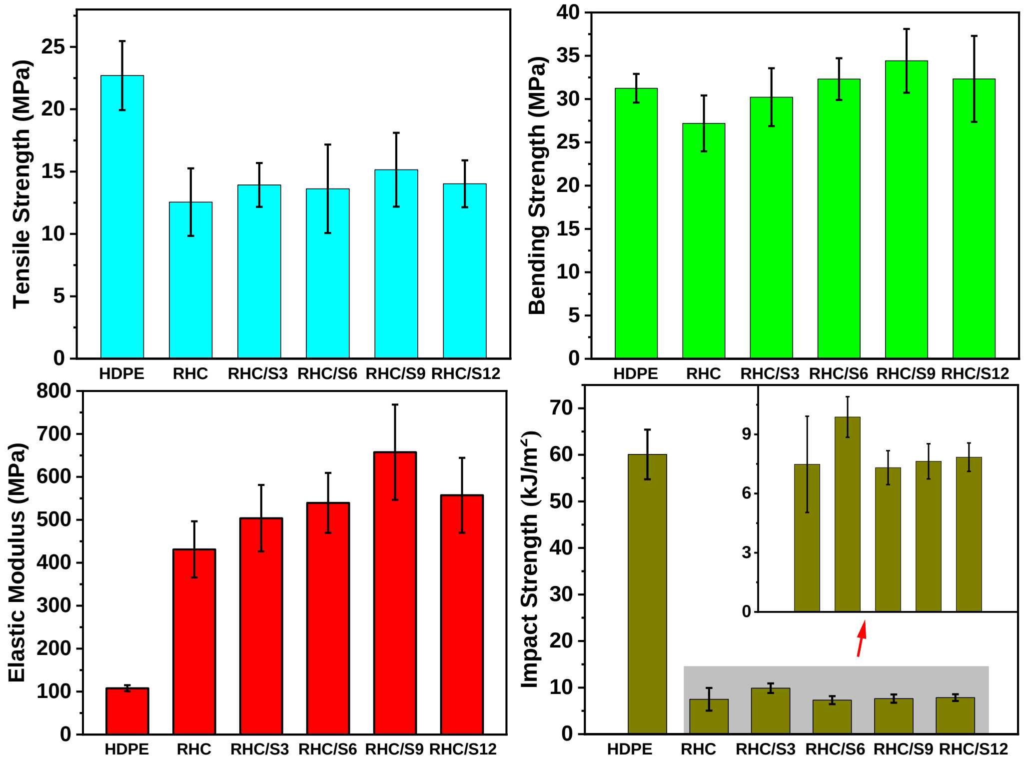

Fig. 1. Mechanical properties of carbon fiber/rice straw-plastic composites

Table 2. Mechanical Properties of Carbon Fiber/Rice Straw-Plastic Composites

Sample	Tensile Strength (MPa)	Impact Strength (MPa)	Bending Strength (MPa)	Flexural Modulus (MPa)	Modulus of Elasticity (MPa)	Elongation at Break (%)
HDPE	22.7 (2.77)	60.08 (5.34)	31.25 (1.66)	783.90 (157.39)	107.80 (7.02)	19.06 (2.56)
RHC	12.55 (2.71)	7.48 (2.44)	27.19 (3.23)	1603.97 (132.52)	431.10 (65.58)	3.91 (1.59)
RHC/S3	13.93 (1.76)	9.88 (1.03)	30.22 (3.34)	1256.34 (174.24)	503.69 (77.47)	3.06 (1.34)
RHC/S6	13.62 (3.55)	7.31 (0.86)	32.31 (2.41)	1543.75 (103.52)	539.45 (69.82)	3.22 (0.62)
RHC/S9	15.15 (2.96)	7.63 (0.89)	34.42 (3.68)	1415.96 (185.78)	657.39 (110.86)	2.64 (0.36)
RHC/S12	14.02 (1.88)	7.84 (0.72)	32.33 (4.97)	1727.88 (417.28)	557.14 (87.29)	2.58 (0.27)

Scanning Electron Microscopy (SEM) Analysis

The interfacial bonding of the RHC with contents of 3% and 9% short carbon fibers under scanning electron microscopy is shown in Fig. 2. Rice straw and HDPE were the main load-bearing parts in the composite materials, which were closely combined and evenly distributed. When the content of carbon fibers was 3%, the rod-like carbon fibers were sparsely distributed in the composites, with smooth surfaces and low roughness. When the content of carbon fibers was 9%, a large number of carbon fibers were surrounded by HDPE matrix, and the fibers are broken, rarely pulled out. This showed that the carbon fibers and composites formed a good interface bonding, which exerted the advantages of a high tensile strength in the carbon fibers and enhanced the tensile strength of the composites. At the same time, a large number of carbon fibers were dispersed unevenly in the matrix, which resulted in no obvious toughening effect of the composites (Lu *et al.* 2013; You and Li 2013; Li *et al.* 2014).

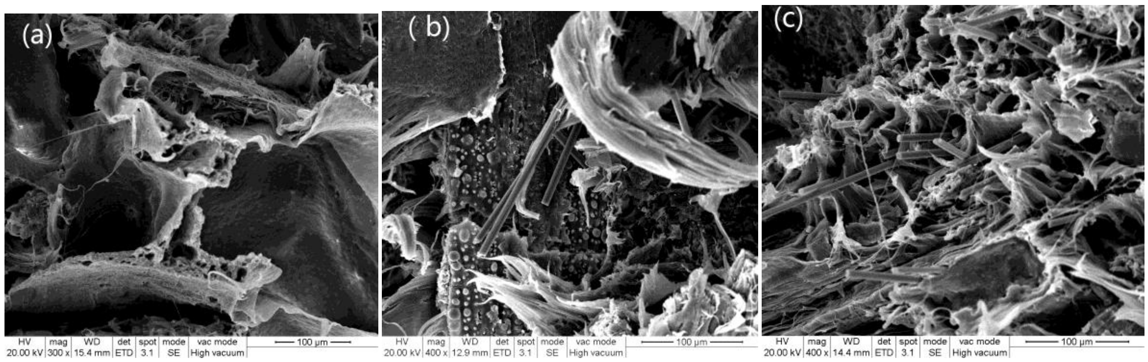

Fig. 2. Micrographs of tensile section of rice straw-plastic composites with different carbon fiber content: (a) RHC, (b) RHC/S3, (c) RHC/S9

Effect of SCF on Creep Properties of Rice Straw-Plastic Composites

Figure 3 shows the effect of different carbon fiber dosages on the creep properties of the RHCs. The creep rate of the RHCs decreased gradually with the extension of time, and the strain increased gradually and before stabilizing. The addition of SCF was beneficial to reduce the deformation of the rice straw wood plastic composites. When SCF was not added, the creep of RHC was 0.16%. When SCF was added, the creep properties of rice straw WPC decreased in varying degrees. When 6% SCF was added, the creep properties of the RHCs reached the lowest value of 0.12%, which was 25% lower than that of the pure rice straw wood-plastic composites.

The main reason was that the HDPE matrix had good toughness, poor stiffness, high flexibility of molecular segments, easy movement, and weak interfacial bonding force. SCF filling can inhibit the movement of the molecular chains of HDPE, strengthening the rigidity of RHCs, reducing creep, and improving the creep properties of RHCs (Wang *et al.* 2007; Du *et al.* 2015; Zhao 2016; Feng and Zhao 2018).

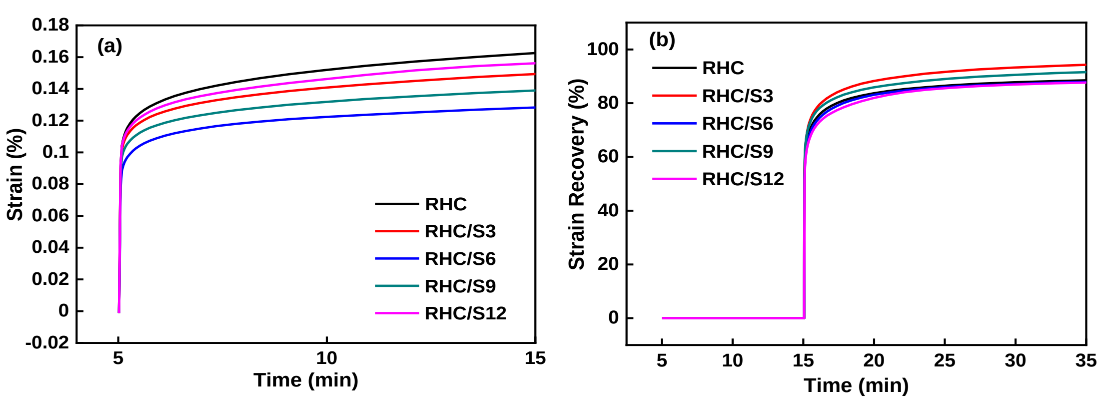

Fig. 3. Effect of different carbon fiber dosage on creep properties of rice straw-plastic composites

FTIR Analysis of Carbon Fiber/Rice Straw-Plastic Composites

Figure 4 shows the FTIR spectrum of rice straw-plastic composites before and after the addition of carbon fiber. The absorption peaks and their attribution results are shown in Table 3. The peak at 730 cm^{-1} was attributed to the vibration of -$(CH_2)_n$- (n⩾4) of polyethylene; The peak at 1030 cm^{-1} was attributed to the stretching vibration of cellulose alkoxy group C-O-R. The peak around 1500 cm^{-1} was attributed to the bending vibration of - CH_2 - in polyethylene. At 2850 cm^{-1} was the symmetric stretching vibration of - CH_2 - in polyethylene. At 2900 cm^{-1} was the asymmetric stretching vibration peak of -CH_2 - in polyethylene. The types of functional groups did not change when carbon fibers were added. The results showed that the skeleton structure of RHC remained after carbon fiber was added.

Table 3. Location and Attribution of Each Absorption Peak in FTIR Spectrum of Rice Straw – Plastic Composites

Wavenumber /cm^{-1}	The ownership of the peak
2900	-CH_2- Asymmetric stretching vibration peak
2850	-CH_2- Symmetric stretching vibration peak
1500	-CH_2- Bending vibration peak
1030	C-O-R Stretching vibration
730	-$(CH_2)_n$- (n≥4) In-plane oscillatory peaks

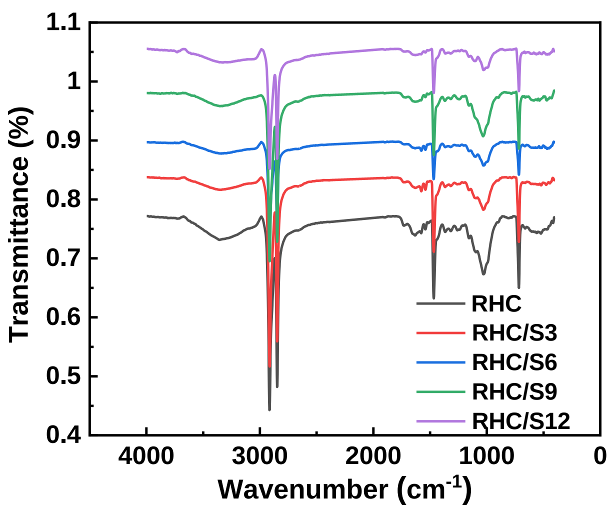

Fig. 4. FTIR spectra of rice straw-plastic composites with different carbon fiber dosages

CONCLUSIONS

Short-cut carbon fiber with different contents was fused and blended with rice straw-plastic composite. The short-cut carbon fiber reinforced rice straw-plastic composite was prepared by the method of molding. The following conclusions were obtained:

1. Scanning electron micrographs showed that the addition of 3% carbon fibers resulted in the rod-like carbon fibers to be sparsely distributed in the composites with smooth

surface and low roughness. When 9% carbon fibers were added, a large number of carbon fibers were surrounded by the high-density polyethylene (HDPE) matrix, and fibers were broken in the course of tensile strength tests, such that they rarely were pulled out. This showed that carbon fiber and composite materials formed good interfacial bonding, so that the tensile strength of the composites was enhanced. At the same time, it was observed that a large number of carbon fibers were dispersed unevenly in the matrix, which resulted in no obvious toughening effect of the composites.

2. When carbon fibers were not added, the creep of RHC was 0.16%. When carbon fibers were added, the creep properties of RHC decreased in varying degrees. When 6% carbon fiber was added, the creep property of RHC/S6 reached the lowest value of 0.12%. Compared with pure rice straw-plastic composite, the creep property of rice straw-plastic composite decreased by 25%. The addition of carbon fiber can reduce the deformation of rice straw-plastic composite (Park and Balatinecz 1998; LabVIEW User Manual 2000; Lee and Kim 2008; Yang *et al.* 2007; Najafi and Kordkheili 2011; Tang *et al.* 2011).
3. The tensile strength of default RHC was 12.55 MPa. When 9% SCF was added, the tensile strength of RHC/S9 reached the maximum value of 15.15 MPa, which was 20.7% higher than that of default RHC, respectively. The flexural strength also showed the same trend as the tensile strength. When the content of carbon fibers was 9%, the flexural strength of the composites increases by 26.5% compared with that of default RHC. The flexural modulus increased by 7.7%, but not significantly. When the content of carbon fiber was 3%, the impact strength of RHC/S3 composite was 32% higher than that of default RHC. When the content of carbon fiber was too high, the distribution of carbon fiber in matrix was uneven and the toughness was not obviously improved.

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