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Preparation and Performance Regulation of Carbon-Fiber-Reinforced PC/ABS Composites for Microwave Absorption and EMI Shielding

WenTao YU[1,2], Jichao DING[3], Liting HAO[3], Lulin WANG[1*], Yeming XIAN[1*]

1. Guangzhou Super-Dragon Engineering Plastics Co.Ltd, Guangzhou, 510440, China

2. College of New Materials and Chemical Engineering, Beijing Institute of Petrochemical Technology, Beijing, 102617, China

3. School of Chemical Engineering, Dalian University of Technology, Dalian, Liaoning, 116024, China

[*] ***Corresponding Author:*** *Lulin WANG, E-mail: hulin@gzselon.com; Yeming Xian, E-mail: xianyeming@gzselon.com*

Abstract

The rapid development of high-frequency electronic devices and fifth-generation wireless communication systems has increased the demand for polymer-based materials with both electromagnetic interference shielding and microwave absorption capabilities. In this work, carbon-fiber-reinforced polycarbonate/acrylonitrile–butadiene–styrene composites were prepared by twin-screw melt compounding, and the effects of carbon fiber content, fiber type, and feeding strategy on the mechanical and electromagnetic properties were investigated. Two feeding modes, namely main feeding and side feeding, were compared to regulate the fiber length distribution and conductive-network structure in the PC/ABS matrix. Compared with main feeding, side feeding effectively reduced fiber breakage during extrusion. For example, the number-average fiber length of MC10%-SF reached 165.7 μm, whereas that of MC10% prepared by main feeding was only 111.7 μm. The retained long fibers promoted the formation of continuous conductive pathways, leading to enhanced dielectric loss and improved electromagnetic attenuation. Among the investigated formulations, MC20%-SF exhibited a maximum reflection loss of -51 dB at 15.5 GHz with a thickness of 1.7 mm and an effective absorption bandwidth of 4.56 GHz. Meanwhile, it maintained favorable mechanical properties, including a tensile strength of 115 MPa and a flexural modulus of 13,249 MPa. For EMI shielding, HC30%-SF achieved a total shielding effectiveness close to 55 dB in the X-band. These results indicate that controlling fiber length through side feeding is an effective strategy for balancing mechanical reinforcement, microwave absorption, and EMI shielding performance in PC/ABS-based conductive composites.

Keywords: *PC/ABS composites; carbon fiber; side feeding; fiber length distribution; microwave absorption; EMI shielding*

1 Introduction

The rapid deployment of fifth-generation wireless communication systems, automotive radar, and high-frequency electronic devices has intensified electromagnetic interference problems in confined electronic environments. Electromagnetic interference not only deteriorates signal transmission quality but may also affect the reliability and safety of electronic components[1]. Therefore, lightweight polymer-based materials capable of electromagnetic interference shielding and microwave absorption have attracted increasing attention. Compared with traditional metallic shielding materials, conductive polymer composites offer advantages such as lower density, easier processing, corrosion resistance, and greater design flexibility.

Polycarbonate (PC) is one of the most widely used engineering thermoplastics owing to its high impact resistance, dimensional stability, heat resistance, and good processability[2]. PC/ABS blends further combine the toughness of PC with the improved melt processability of ABS, making them suitable for housings and structural components in electronic and

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automotive applications. However, both PC and PC/ABS are electrically insulating and exhibit limited electromagnetic wave attenuation. Introducing conductive fillers into PC/ABS matrices is therefore an effective route to impart electromagnetic functionality while retaining the advantages of thermoplastic processing.

Carbon fibers are promising conductive fillers because of their high aspect ratio, electrical conductivity, thermal stability, and mechanical reinforcement capability. When dispersed in a polymer matrix, carbon fibers can form interconnected conductive networks, which contribute to conduction loss, interfacial polarization, and multiple reflection of electromagnetic waves[3-4]. However, the final electromagnetic performance of carbon-fiber-reinforced polymer composites is strongly influenced by the fiber length, dispersion state, and interfacial morphology. During melt compounding, excessive shear may cause severe fiber breakage, reducing the effective aspect ratio and increasing the percolation threshold. As a result, the construction of an efficient conductive network in PC/ABS composites remains challenging.

In this study, carbon-fiber-reinforced PC/ABS composites were prepared by twin-screw extrusion. The effects of carbon fiber content and feeding strategy were systematically investigated. In particular, main feeding and side feeding were compared to clarify the role of fiber length retention in determining mechanical properties, dielectric response, microwave absorption, and EMI shielding effectiveness. The relationship among processing, microstructure, and electromagnetic performance was analyzed to provide a practical strategy for preparing multifunctional PC/ABS composites for high-frequency electronic applications.

2 Experimental

2.1 Materials

Polycarbonate resin was supplied by Mitsubishi Engineering-Plastics Corporation. Acrylonitrile–butadiene–styrene resin was obtained from LG Chem. Two commercial carbon fibers, CFUW-MC C-6 and CFEPU-HC C-6, supplied by Toray Industries, were used and denoted as MC and HC, respectively. Carbon black was used as a secondary conductive filler. Irganox 168 and Irganox 1076 were used as antioxidants. A methyl methacrylate–butadiene–styrene copolymer was employed as the toughening agent, and pentaerythritol tetrastearate was used as the lubricant. All materials were dried according to standard processing requirements before extrusion.

2.2 Composite preparation

PC/ABS/CF composites were prepared by melt compounding using a co-rotating twin-screw extruder with a screw diameter of 35 mm and an L/D ratio of 40:1. The formulations are listed in Table 1. PC, ABS, carbon black, antioxidants, toughening agent, and lubricant were premixed in a high-speed mixer and introduced through the main hopper. For the main-feed samples, carbon fibers were also fed through the main hopper and therefore experienced the entire screw shear history. For the side-feed samples, carbon fibers were introduced through a downstream side feeder to reduce their residence time and shear exposure. The barrel temperature was set between 220 and 260 ℃ from the feeding zone to the die, and the screw speed was maintained at 300 rpm. The extrudates were water-cooled, pelletized, and dried at 120 ℃ for 4 h before injection molding and characterization.

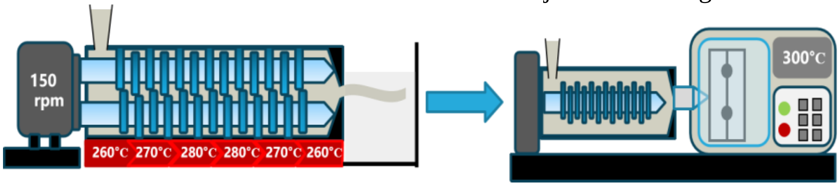

Figure 1 Schematic diagram of preparation process flow of PC/ABS/CF composites

Table 1 Formulations of PC/ABS/CF composites (wt%)

Sample	PC	ABS	CF (MC)	CF (HC)	CB	Antioxidants	Toughener	Lubricant
PC/ABS	65.8	28.2	—	—	2.5	0.3	3.0	0.2
MC10%	58.8	25.2	10	—	2.5	0.3	3.0	0.2
MC20%	51.8	22.2	20	—	2.5	0.3	3.0	0.2
MC30%	44.8	19.2	30	—	2.5	0.3	3.0	0.2
HC10%	58.8	25.2	—	10	2.5	0.3	3.0	0.2
HC20%	51.8	22.2	—	20	2.5	0.3	3.0	0.2
HC30%	44.8	19.2	—	30	2.5	0.3	3.0	0.2

3 Characterization

3.1 Mechanical properties

The PC/ABS/CF composites undergo preparation via melt compounding using a co-rotating twin-screw extruder (screw diameter: 35 mm, L/D ratio: 40:1). The formulations appear in Table 1. PC, ABS, carbon black, antioxidants, a toughening agent, and a lubricant mix in a high-speed mixer and feed through the main hopper. In the main-feed series, carbon fibers also enter through the main hopper alongside the other components, exposing the fibers to the full screw shear history. In the side-feed series, carbon fibers are introduced separately through a side-feed. The mechanical properties of the PC/ABS/CF composites are summarized in Table 2. With the increase in the amount of carbon fiber added, the rigidity of the material increases while its toughness decreases, manifested as an increase in strength modulus and a decrease in elongation. When carbon fiber is added through side feeding and the content is below 30%, the mechanical properties of the material exhibit the same trend. However, when the content reaches 30%, the mechanical properties decline, which is caused by poor compatibility between the matrix and carbon fiber.

3.2 Morphology and fiber length distribution

The fracture surfaces of the composites after cryogenic fracture were examined by scanning electron microscopy. Before observation, the specimens were sputter-coated with a thin layer of gold to reduce charging. For fiber length analysis, the polymer matrix was removed by dissolution in dichloromethane, and the extracted fibers were collected, dispersed on glass slides, measured from optical microscopy images and used self-developed software to count and calculate the length[5]. At least 300 fibers were counted for each sample to obtain representative length distributions.

We extracted fibers from the composites and measured their length distributions (Table 3). For MC10%, main-feeding gave a number, average length of 111.7 μm; side-feeding raised it to 165.7 μm. The improvement persisted at 20 wt% (106.0→146.4 μm) and 30 wt% (97.2→134.9 μm). Weight-average and cubic-average lengths followed the same trend. In both feeding modes, increasing fiber content reduced average length, which we link to higher melt viscosity and more frequent fiber-fiber collisions that cause breakage. But the distribution width remained narrow (1.20-1.30), indicating that side-feeding shifts the whole distribution toward longer values rather than creating a bimodal population. SEM images (Figure 2) visually confirm this: Longer retained fibers provide a higher effective aspect ratio, improve the continuity of the reinforcing network, and enhance load transfer within the PC/ABS matrix. This explains why the side-feed composites exhibited better tensile and flexural properties than the main-feed composites at the same carbon fiber content.

Table 2 Mechanical properties of PC/ABS/CF composites.

	Tensile strength / MPa	Elongation at break/ %	Impact strength / kJ m^{-2}	Flexural strength / MPa	Flexural modulus / MPa
Pure PC/ABS	54	29.7	43.4	86.6	2442
MC 10%	64.9	5.3	5.79	102.7	4538
MC 20%	72.1	4.2	4.39	113	6736
MC 30%	96.4	3.85	4.12	144	11742
HC 10%	60.8	6.1	5.59	97.1	3987
HC 20%	68.5	4.8	4.08	123	9668
HC 30%	81.3	3.6	3.46	110	6567
MC 10%-SF	95.4	3.8	7.14	137.4	7731
MC 20%-SF	115	3.6	6.59	173.8	13249
MC 30%-SF	114	3.7	6.88	162.3	10756
HC 10%-SF	84.5	3.9	6.87	143	8297
HC 20%-SF	109	3.3	5.92	176	13781
HC 30%-SF	114	3.6	6.33	166.2	10751

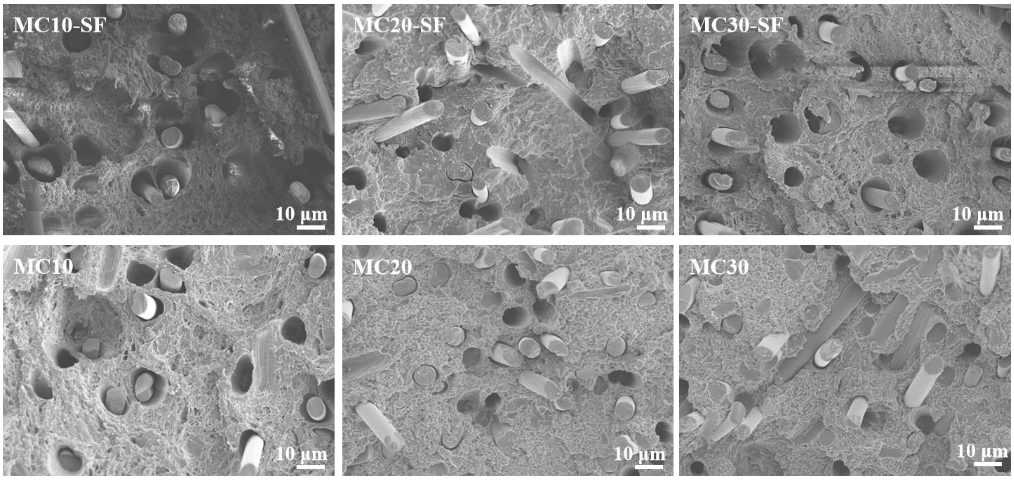

Figure 2 The SEM image of PC/ABS/CF composites

Table 3 Fiber length distribution parameters of carbon fibers extracted from composites.

	Number-average Length/μm	Weight-average Length/μm	Mean Cubic Length/μm	Distribution Width
MC10%-SF	165.67	206.3	247.27	1.25
MC20%-SF	146.37	175.67	204.92	1.2
MC30%-SF	134.94	175.27	215.24	1.3
MC10%	111.72	134.84	161.23	1.21
MC20%	106.02	135.28	177.45	1.28
MC30%	97.21	116.49	140.83	1.2

3.3 Dielectric properties

The complex permittivity of the composites was measured in the frequency range of 2-18 GHz using a vector network analyzer and the coaxial transmission-line method. The specimens were machined into circular ring samples with an outer diameter of 7.0 mm, an inner diameter of 3.0 mm, and a thickness of 2.0-3.0 mm.

The complex permittivity (ε′ and ε″) of the composites in the 2-18 GHz range appears in Figure 3. Because no magnetic components are included in the formulations, the complex permeability (μ′ and μ″) remains approximately 1.00 and 0.00, respectively, throughout the entire frequency range. Consequently, the electromagnetic wave attenuation of these composites is primarily determined by dielectric loss rather than magnetic loss.

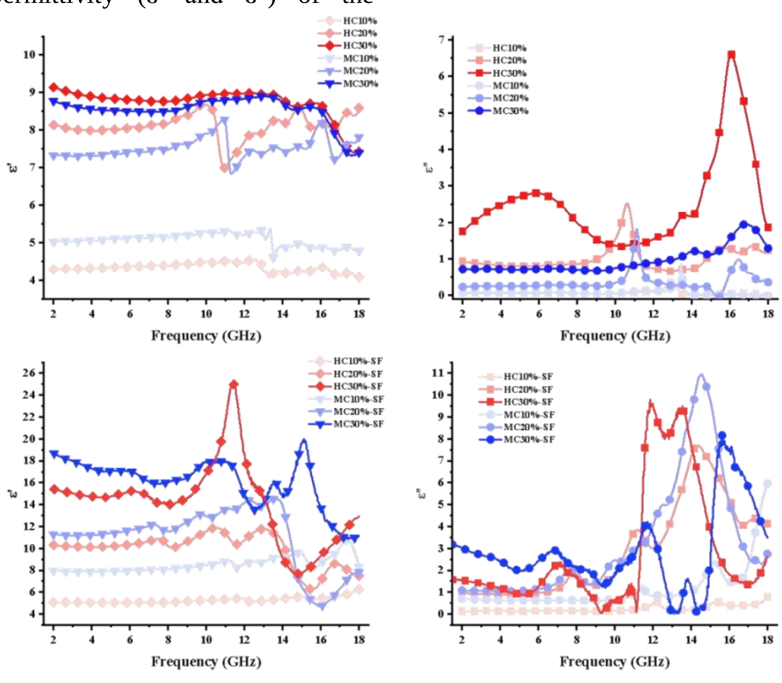

Figure 3 The complex permittivity of PC/ABS/CF composites

Both the real (ε′) and imaginary (ε″) parts of the permittivity increased with increasing CF content, consistent with the enhanced polarization and conductive loss contributions from the carbon fibers. The side-feed series exhibited significantly higher permittivity values than the main-feed series at equivalent CF loading. For example, at 10 GHz, ε′ for MC20%-SF reached approximately 25, compared to ~15 for MC20% (main-feed). This enhancement is attributed to the longer fibers in the side-feed composites, which more readily form conductive pathways and facilitate charge transport within the matrix.

3.4 EMI Shielding effectiveness

The scattering parameters (S_{11} and S_{12}) of the composites were measured using the waveguide method over the X-band frequency range (8.0-12.6 GHz). The EMI shielding effectiveness (SE), including total shielding effectiveness (SE_T), absorption (SE_A), and reflection (SE_T), was calculated from the scattering parameters according to the following equations[6]:

$$R = |S_{11}|^2,\ \ T = |S_{21}|^2,\ \ A = 1 - R - T \quad (1)$$

$$SE_T = SE_R + SE_A + SE_M \quad (2)$$

$$SE_R = -10\log_{10}(1 - R) \quad (3)$$

$$SE_A = -10\log_{10}\left[\frac{T}{1 - R}\right] \quad (4)$$

The EMI shielding effectiveness of the composites was evaluated in the X-band, and the results are shown in Figure 5. The total shielding effectiveness increased with increasing carbon fiber content for both the main-feed and side-feed series. At the same filler loading, the side-feed composites exhibited higher shielding effectiveness than the main-feed composites, which can be attributed to the more continuous conductive networks formed by the longer retained fibers.

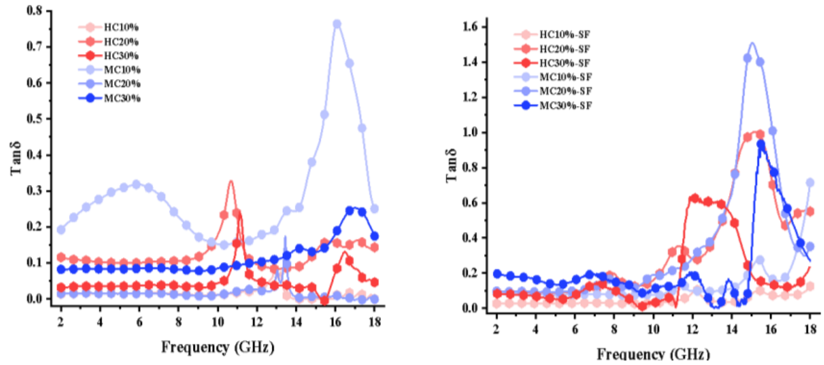

Figure 4 The dielectric loss tangent of PC/ABS/CF composites

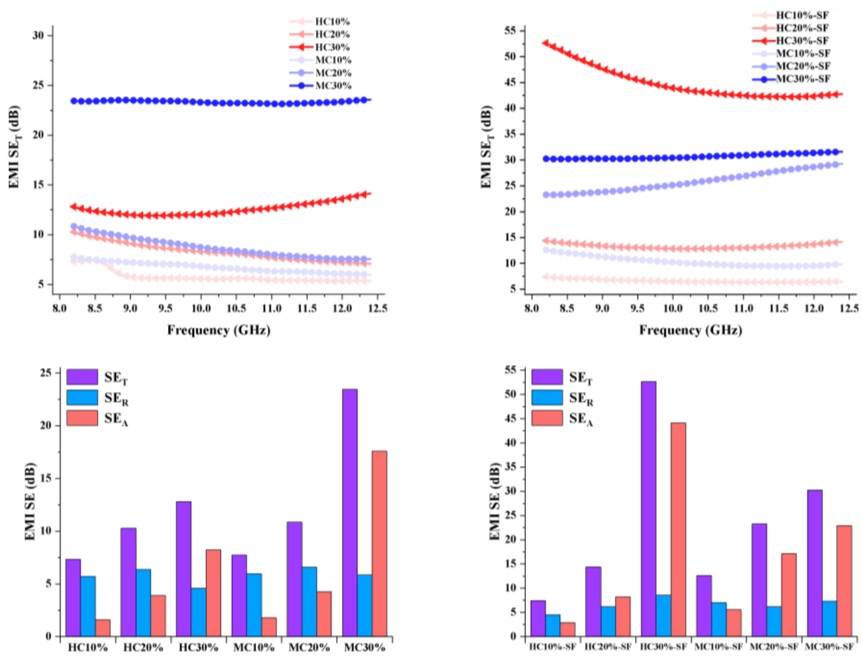

Figure 5 The shielding effectiveness of PC/ABS/CF composites

Among all samples, HC30%-SF achieved a total shielding effectiveness close to 55 dB at 10 GHz. This value is sufficient for many practical EMI shielding applications. The enhanced shielding performance originates from the combined effects of reflection and absorption. At low carbon fiber loading, reflection contributes significantly to the total shielding because of the impedance mismatch between air and the conductive composite surface. As the carbon fiber content increases, the conductive network becomes denser, and absorption gradually becomes the dominant shielding mechanism. The increased absorption contribution is related to ohmic loss, interfacial polarization, and multiple scattering within the interconnected fiber network.

The transition from reflection-dominated shielding to absorption-dominated shielding is beneficial for electromagnetic compatibility applications because absorption can reduce secondary electromagnetic pollution caused by reflected waves. Therefore, side feeding not only improves the magnitude of shielding effectiveness but also promotes a more favorable shielding mechanism.

3.5 Microwave absorption performance

The reflection loss (RL) of the composites was calculated from the measured electromagnetic parameters using the transmission-line theory. For a single-layer absorber backed by a perfect conductor, the input impedance (Z_{in}) at the absorber surface is given by the following equations[7]:

$$Z_{in}=Z_0\sqrt{\mu_r\varepsilon_r}\tanh\left[j\left(\frac{2\pi fd}{c}\right)\sqrt{\frac{\mu_r}{\varepsilon_r}}\right] \tag{5}$$

$$RL=20lg\left|\frac{Z_{in}-Z_0}{Z_{in}+Z_0}\right| \tag{6}$$

where f is the frequency, d is the absorber thickness, c is the speed of light, and Z_0 is the impedance of free space (377 Ω). The RL values were calculated for absorber thicknesses ranging from 1.0 to 5.5 mm to identify the optimal thickness for maximum absorption at each frequency.

The microwave absorption performance of the composites was evaluated by calculating the reflection loss based on transmission-line theory. The maximum reflection loss, corresponding matching thickness, matching frequency, and effective absorption bandwidth are summarized in Table 4. The neat PC/ABS blend exhibited negligible microwave absorption, with a reflection loss of approximately -2 dB, confirming that the polymer matrix itself has limited electromagnetic attenuation capability.

As shown in the Table 4, the addition amount and dispersion length of SE_T are directly proportional to the amount of carbon fiber added. For the side-feeding series, HC30% SE_T can reach nearly 55 dB. According to the SE distribution diagram of the sample at a frequency of 8.0 GHz, when the carbon fiber content is between 10% and 20%, SE is mainly contributed by SE_R ($SE_R > SE_A$), indicating that the electromagnetic shielding of the sample is achieved through both electromagnetic wave reflection and absorption, with a higher proportion of reflection. When the content is at 30%, SE is mainly contributed by SE_A, and electromagnetic shielding is mainly achieved through electromagnetic wave absorption. The same trend is even more pronounced in the side-feeding system. When the addition reaches 20%, SE_A has already begun to exceed SE_R, indicating that when carbon fibers form a conductive network in the matrix, they can absorb electromagnetic waves through conductivity loss, thus achieving better electromagnetic shielding performance. Therefore, the electromagnetic wave absorption (wave absorption) of the sample and the influence of carbon fiber distribution and dispersion length on the material's wave absorption behavior must be explored in detail.

Table 4 Microwave absorption properties of PC/ABS/CF composites.

	Maximum Reflection Loss/dB	Effective Absorption Bandwidth/ GHz
Pure PC/ABS	-2	-
MC 10%-SF	-40 (4.7 mm,17.0 GHz)	1.76
MC 20%-SF	-51 (1.7 mm,15.5 GHz)	4.56
MC 30%-SF	-45 (4.6 mm,14.2GHz)	4.80
HC 10%-SF	-11 (5.3 mm,18.0 GHz)	-
HC 20%-SF	-52 (1.6 mm,15.8 GHz)	3.68
HC 30%-SF	-39 (1.6 mm,11.2 GHz)	2.80
MC 10%	-5.7	-
MC 20%	-15 (5.2 mm,16.4 GHz)	0.96
MC 30%	-54 (2.4 mm,7.7 GHz)	4.80
HC 10%	-5.57	-
HC 20%	-21 (5.4 mm,15.6 GHz)	1.60
HC 30%	-46 (2.7 mm,7.2 GHz)	4.64

Therefore, the improved absorption performance of MC20%-SF and HC20%-SF can be attributed to a better balance between impedance matching and attenuation capability. The results demonstrate that side feeding is an effective processing strategy for preparing PC/ABS/CF composites with both good microwave absorption and EMI shielding properties.

4 Conclusion

In this work, carbon-fiber-reinforced PC/ABS composites were prepared by twin-screw melt compounding, and the influence of feeding strategy on fiber length retention, mechanical properties, dielectric behavior, microwave absorption, and EMI shielding performance was investigated. Compared with main feeding, side feeding effectively reduced fiber breakage during extrusion and preserved longer carbon fibers in the PC/ABS matrix. The number-average fiber length of MC10%-SF reached 165.7 μm, which was much higher than that of the corresponding main-feed sample.

The retained long fibers enhanced the formation of conductive networks and improved both mechanical reinforcement and electromagnetic attenuation. MC20%-SF exhibited a tensile strength of 115 MPa and a flexural modulus of 13,249 MPa, showing a significant improvement over the main-feed counterpart. In terms of microwave absorption, MC20%-SF achieved a maximum reflection loss of -51 dB at 15.5 GHz with a thickness of 1.7 mm and an effective absorption bandwidth of 4.56 GHz. For EMI shielding, HC30%-SF showed a total shielding effectiveness close to 55 dB in the X-band.

The results demonstrate that the feeding strategy is a key processing parameter for regulating the fiber length distribution and conductive-network structure in PC/ABS/CF composites. Side feeding enables a favorable balance among mechanical strength, microwave absorption, and EMI shielding performance, making the prepared composites promising candidates for high-frequency electronic devices, 5G communication equipment, and automotive electromagnetic protection applications.

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