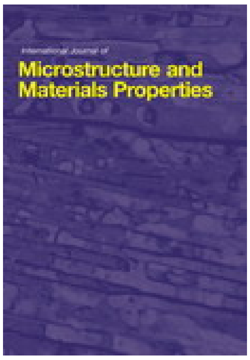

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Preparation and electrical properties analysis of waterborne epoxy resin carbon nanotube composite materials

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Abstract: Using multi-walled carbon nanotubes and waterborne epoxy resin as raw materials, a waterborne epoxy resin carbon nanotube composite material specimen was prepared. The effects of the amount of multi-walled carbon nanotubes and montmorillonite, as well as shear time, on the electrical properties of the composite material were analysed. The conductivity and dielectric loss is analysed through a broadband dielectric impedance spectrometer. Then, a high resistance meter is used to test surface and volume resistivity. Finally, the mechanical and electrical performance is analysed through a universal testing machine combined with the four electrode method. The experimental results show that extending the stirring time can reduce the surface resistivity of composite materials and improve their conductivity; increasing the amount of multi-walled carbon nanotubes can reduce surface resistivity; increasing the amount of montmorillonite appropriately can improve the dielectric constant of the material.

Keywords: waterborne epoxy resin; carbon nanotubes; preparation of composite materials; electrical performance analysis; conductivity; surface resistivity.

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1 Introduction

The cylindrical shell composed of spiral arrangement of carbon atoms is called carbon nanotubes. The diameter of carbon nanotubes is on the nanoscale, and the entire shell can be composed of several layers of carbon atoms arranged (Blokhin et al., 2020). Carbon nanotube materials have good electrical and mechanical properties (Ye et al., 2020). With the development of materials science, carbon nanomaterials, combined with other materials, are widely used in various fields such as component manufacturing, fault diagnosis, radar, etc. (Bilisik and Syduzzaman, 2021). Waterborne epoxy resin has strong adhesion, and when used for coating, its shrinkage is small, and its hardness and wear resistance are also strong (Tian et al., 2020). The dispersion medium of waterborne epoxy resin is water, which has good stability and safety during use and transportation. The composite material formed by combining waterborne epoxy resin and carbon nanotubes not only retains the advantages of waterborne epoxy resin, but also combines the conductivity and mechanical properties of carbon nanotubes (Shcherbakov et al., 2021). After combining waterborne epoxy resin with carbon nanotubes, the waterborne epoxy resin matrix adhered to the surface of carbon nanotubes aggregates the carbon atoms on the surface of carbon nanotubes, making the carbon nanotube material dispersible and effectively improving the conductivity of the waterborne epoxy resin carbon nanotube composite material (Oh et al., 2020). Due to its unique structure, carbon nanotubes are widely used in high-tech industries such as aerospace and monitoring (Ji et al., 2020). However, due to the dispersion limitation of carbon nanotubes, their application effectiveness is lacking. In order to improve the application performance of carbon nanotubes, they are combined with waterborne epoxy resin to form a composite material, which greatly improves the application range and effectiveness of carbon nanotubes and waterborne epoxy resin (Isarn, 2020). Suarez-Riera et al. in order to ensure good dispersion of waterborne epoxy resin carbon nanotube composites in water and strong interaction with cement, the best oxidation treatment method is to modify the surface of carbon nanotubes with polar groups in a solution of sulfuric acid and nitric acid. The processing time can affect the electrical properties of composite materials, and this method deeply analyses the effect of processing time on waterborne epoxy resin carbon nanotube composite materials. Research has shown that prolonged oxidation treatment (90 minutes) is very effective in obtaining well dispersed carbon nanotubes, which enables us to obtain cement-based composites with better electrical properties than ordinary cement (Suarez-Riera et al., 2022).

Suleimanov et al. studied the conductivity of epoxy resin doped functionalised single walled carbon nanotubes (SWNTs) composite materials under constant and alternating electric fields, and observed that the maximum conductivity temporarily shifted with the increase of electric field amplitude. The results indicate that during the current flow through the sample, there is competition between the aggregation and orientation processes of carbon nanotubes in the external electric field. This competition promotes the growth of conductivity, the polymerisation process, and the migration of carbon nanotubes in the polymer matrix becomes complex. Research has found that the efficiency of external direct and alternating electric fields increases with the decrease of carbon nanotube concentration, and alternating electric fields are more suitable for forming permeable structures in materials (Suleimanov et al., 2022). Turan et al. investigated the effects of composition changes and process parameters on the electrical properties of epoxy based composites filled with carbon nanomaterials. Using expanded graphite (EG) as a filling material for epoxy resin matrix, the influence of the geometric characteristics of carbon fillers on the physical properties of epoxy resin was investigated. The effects of hole content and agglomeration size (carbon nanotube content, dispersion level, functionalisation degree, and surface area) on the electrical properties of composite materials were studied. According to conductivity measurements, the permeation threshold of carbon nanotubes is 0.1 wt%. High power and long-term ultrasonic treatment have adverse effects on the electrical properties of carbon nanotubes, which is due to the length fracture of carbon nanotubes; the conductivity of composite materials increases with the increase of carbon nanotube load, but larger clumps are generated. The conductivity of graphene filled nanocomposites is lower than that of original carbon nanotubes and functionalised carbon nanotubes (f-CNTs) reinforced epoxy nanocomposites (Turan et al., 2022). Samankan et al. investigated the relationship between the properties of polymers as the basic material for nanocomposites and the strengthening effect of MWCNTs. Prepare standard specimens of pure resin and reinforced resin using 0.5 wt% MWCNTs. The results indicate that the presence of MWCNT greatly improves the conductivity of vinyl esters and epoxy resins; for polyester resin, the addition of MWCNT did not significantly improve its performance (Samankan et al., 2021).

However, the above methods only analysed a single influencing factor and did not fully study the interference factors of the electrical properties of composite materials. To this end, the preparation and electrical performance analysis methods of waterborne epoxy resin carbon nanotube composites were studied, and factors such as multi-walled carbon nanotube content and stirring time were analysed to determine their impact on their electrical properties. The overall research idea of this method is as follows:

1 The selected raw materials are reagents such as multi-walled carbon nanotubes, montmorillonite, and triethanolamine.

2 Using instruments such as a vacuum drying oven and a high-speed desktop centrifuge, the processed multi-walled carbon nanotubes and other reagents were processed to prepare composite material specimens with different amounts of multi-walled carbon nanotubes and montmorillonite. These specimens were used to analyse the effects of the amounts of multi-walled carbon nanotubes and montmorillonite on the electrical properties of composite materials.

3 The stirring time during preparation is 1–10 minutes, and the shear time is 10 minutes, 20 minutes, and 30 minutes. This is used to analyse the impact of different stirring and shear times on the electrical properties of composite materials.

4 Using a high resistance meter to test the surface, volume resistivity, and current density field strength characteristics of composite materials; analyse the electrical erosion resistance time of the composite material using two stainless steel needle tip electrodes; analyse the mechanical and electrical properties of composite materials using a universal testing machine combined with the four electrode method.

5 Through experimental analysis, it can be concluded that increasing the amount of multi-walled carbon nanotubes can reduce the surface resistivity of composite materials, enhance their breakdown field strength and dielectric constant, and enhance their conductivity. The minimum surface resistivity is around 10^6 Ω·cm, the maximum breakdown field strength is around 28.9 kV/mm, and the maximum dielectric constant is around 52. An appropriate increase in the amount of montmorillonite can reduce the volume resistivity of the composite material, improve the breakdown field strength and dielectric constant. The optimal amount of montmorillonite is 6.2%, and to improve the insulation performance of the composite material, the optimal amount of montmorillonite is 6.4%. Extending the shear time can improve conductivity and extend the resistance to electrical erosion.

2 Materials and methods

2.1 Selection of reagents and instruments

The test reagents required for the preparation of waterborne epoxy resin carbon nanotube composite materials are shown in Table 1.

The test instruments are shown in Table 2.

Table 1 Test reagents

Reagent name	*Chemical formula*	*Molecular weight*	*Specification/grade*	*Manufacturer*
Multi-walled carbon nanotubes (MWCNT)	-	-	Content ≥ 99.9%, particle size 10 nm/5–10 µm	Nano Technology Corporation
Montmorillonite (MMT)	$(Al, Mg)_2[SiO_{10}](OH)_2nH_2O$	-	Active white soil, grain size 10–1,200 mesh	Yibang building Materials Marketing Department
Tween-80	$C_{24}H_{44}O_6$	428.6	Analytical pure, amber thick liquid	Hai An Shi Petrochemical
Triton-114	$C_{34}H_{62}O_{11}$	646.86	Analytically pure, colourless viscous liquid	This Morning Chemical Company
Waterborne epoxy resin	-	138.92	Colourless liquid, epoxy value 0.49~0.55	Huakai Resin Company
Triethanolamine	$C_6H_{15}NO_3$	149.1882	Purity > 99%	Xinru Li Chemical Technology Company
Methyl tetrahydrophthalic anhydride	$C_9H_{10}O_3$	166.181	Purity > 99%	Qihua Chemical Company
Concentrated nitric acid	HNO_3	63	Analytical pure	Reisehing Technology Company
Concentrated sulphuric acid	H_2SO_4	98.04	Analytical pure	Reisehing Technology Company
Acetone	CH_3COCH_3	58.08	Analytical pure	Huihai Technology Corporation

Table 2 Test instruments

Test instrument	*Model number*	*Manufacturer*
Ultrasonic cleaner	BQS-1020	Bopper company
Bidirectional magnetic agitator	ST-II	North Tongzheng Biotechnology Company
Electronic analytical balance	FA1004N	Tuoxi Electric Subsidiary
High temperature sintering furnace	WLT-17RK	Wilter Furnace Co. Ltd
Vacuum drying oven	DZF6050	Yiheng Manufacturing Company
High speed shear dispersing emulsifier	XN-RHG500	Calf Light Industrial Machinery Company
Wide-band dielectric impedance spectrometer	H6258-25G	Beiguang Precision Instrument Company
Breakdown voltage tester	BDJC-20kV	Beiguang Precision Instrument Company
Ultrasonic reactor	AIR-5L	Ouhe Machinery Equipment Co. Ltd
High resistance metre	HEST-200	China Test Instrument Company
Universal testing machine	WAW-300D	Yongning Equipment and Instrument Company

2.2 Preparation of waterborne epoxy resin carbon nanotube composite materials

Before preparing waterborne epoxy resin carbon nanotube composites, it is necessary to purify, oxidise, and functionalise multi-walled carbon nanotubes (Xie et al., 2022).

The purification process steps for multi-walled carbon nanotubes are as follows:

Step 1 Pour 300 mL of concentrated nitric acid into a circular flask with a capacity of 2.5 L, and add an appropriate amount of water to dilute the concentrated nitric acid. After dilution, the capacity of the concentrated nitric acid is 2.5 L, and continuous stirring is required during the dilution process.

Step 2 Add multi-walled carbon nanotubes (Lu et al., 2022) to the diluted concentrated nitric acid and heat the flask. When the temperature reaches 65°C, stir the solution and reflux for 36 hours before starting to cool the solution.

Step 3 After the cooling is completed, the solid liquid inside the flask is separated, and the clear liquid and floating solids on the upper part of the flask are poured out, leaving behind black solids.

Step 4 Use deionised water to repeatedly rinse the remaining black solid until it is neutral.

Step 5 Adjust the temperature of the vacuum drying oven to 85°C, vacuum dry the black filter cake for 4.5 hours, and grind and store the filter cake for later use.

The oxidation treatment steps for multi-walled carbon nanotubes are as follows:

Step 1 Mix concentrated sulphuric acid and concentrated nitric acid in a 3:1 ratio to obtain a concentrated acid mixture. Place purified multi-walled carbon nanotubes in this liquid (Avil, 2020).

Step 2 Use an ultrasonic cleaner to process the solution obtained in step 1, with a temperature and time of 45°C and 3.5 hours, respectively. After ultrasonic treatment, let the solution stand and pour out the upper clear liquid.

Step 3 Repeat rinsing the remaining suspension with deionised water until the suspension is neutral. Adjust the temperature of the vacuum drying oven to 85°C and vacuum dry the suspension for 4.5 hours. After drying, grind and store it for future use.

The functionalisation treatment steps for multi-walled carbon nanotubes are as follows:

Step 1 Use an electronic Analytical balance to weigh 500 mg of Tween-80 and Triton-114.

Step 2 Add Tween-80 and Triton-114 to 250 mL of water, and add oxidised multi-walled carbon nanotubes.

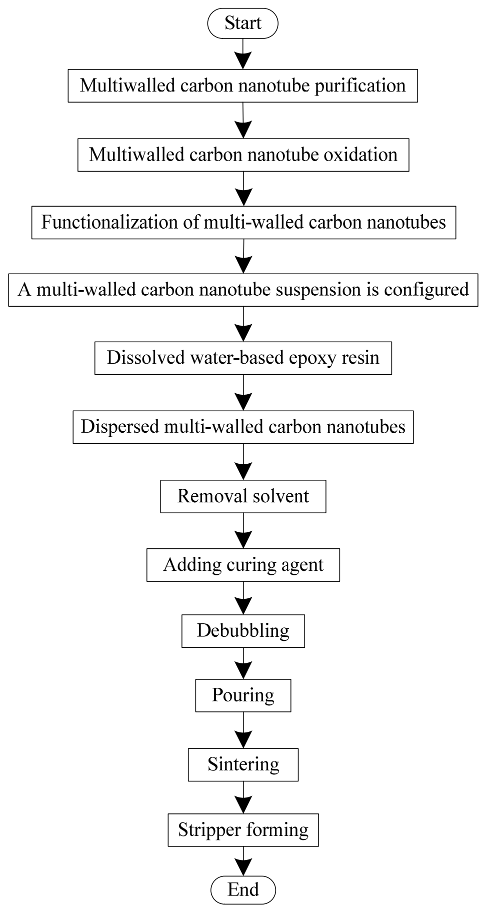
Step 3 Use a high-speed shear dispersion emulsification machine to shear and disperse the solution obtained in step 2, with a shear dispersion time of 1.5 hours.

Step 4 Using a high-speed desktop centrifuge at a speed of 7,500 rpm/min, centrifuge the dispersed solution in step 3 and remove the undispersed multi-walled carbon nanotubes (Marjanovi et al., 2021) for 10 minutes.

Step 5 Place the product obtained in step 4 in a vacuum drying oven at 85°C for 10 hours to obtain functionalised multi-walled carbon nanotubes (Karkhanehchin et al., 2021).

The preparation process of composite materials is shown in Figure 1.

Figure 1 Preparation process of composite materials



The specific steps for preparing waterborne epoxy resin carbon nanotube composite materials are as follows:

Step 1 Purification, oxidation, and functionalisation of multi-walled carbon nanotubes.

Step 2 Prepare MWCNT suspension. Add MWCNT, acetone, and montmorillonite to the container and stir for 5 minutes. The ultrasonic reactor is used to vibrate and stir the uniform solution for 25 min, so that MWCNT is evenly dispersed in acetone solvent to obtain suspension.

Step 3 Dissolve waterborne epoxy resin. Add waterborne epoxy resin into the suspension, and use a two-way magnetic stirrer to stir evenly for 1 min–10 min, so that the waterborne epoxy resin can be completely dissolved in the suspension.

Step 4 Disperse multi-walled carbon nanotubes. Use a high-speed shear dispersion emulsification machine to disperse and treat multi-walled carbon nanotubes, with a shear speed of 5,000 r/min and a shear time of 10 min, 20 min, and 30 min, until there are no significantly viscous clumps in the solution.

Step 5 Remove the solvent. Place the dispersed solution into a container and heat it in a high-temperature sintering furnace to evaporate the solvent.

Step 6 Add curing agent. Add methyltetrahydrophthalic anhydride and triethanolamine to the mixture after removing the solvent, and stir evenly using a bidirectional magnetic stirrer.

Step 7 Remove bubbles. After adding methyltetrahydrophthalic anhydride and triethanolamine, a large number of bubbles will appear in the mixture. A high-speed desktop centrifuge is used to centrifuge the mixture and remove the bubbles.

Step 8 Pouring. Pour the mixture that removes bubbles into the mould, and after pouring for a period of time, the mixture will automatically solidify.

Step 9 Sintering. Heat the solidification solution in a high-temperature sintering furnace to obtain a cured waterborne epoxy resin carbon nanotube composite material specimen.

Step 10 Demoulding and forming. Take out the sintered specimen in the high-temperature sintering furnace.

When preparing waterborne epoxy resin carbon nanotube composite materials, the dosage of multi-walled carbon nanotubes is 1%, 5%, and 10%, respectively; the dosage of montmorillonite is 0%, 6.1%, 6.2%, 6.3%, and 6.4%, respectively.

In order to achieve the optimal composition ratio in the preparation of waterborne epoxy resin carbon nanotube composites, several factors need to be considered. Firstly, the formulation should be determined based on the purpose and requirements of the composite material. Secondly, the composition should be optimised by experimenting with different ratios and testing the performance of the composite material, such as strength, wear resistance, and corrosion resistance. Thirdly, the production process should be strictly controlled to ensure the accuracy of each component's addition and timing. Fourthly, the compatibility between the resin, carbon nanotubes, and additives should be considered to avoid affecting the performance of the composite material. Finally, referencing relevant literature and empirical data can provide valuable guidance for adjusting and optimising the composition ratio during the preparation process. By taking into account these factors, it is possible to achieve the best composition ratio and produce high-quality waterborne epoxy resin carbon nanotube composites.

2.3 Electrical performance analysis methods

Analyse the conductivity, dielectric constant, and dielectric loss of the specimen using a broadband dielectric impedance spectrometer, with a frequency range of 50 Hz~500 Hz

(Sazgar et al., 2022). Let the percolation threshold be p_z, and the conductivity formula is as follows:

$$\alpha = \alpha_0 \left(p - p_z \right)^t \tag{1}$$

Among them, the conductivity of the specimen and substrate is α and α_0; the quality score is p; the coefficient is t.

The calculation formula for p_z is as follows:

$$p_z \propto \frac{32\pi R^3}{3} \left[1 + \frac{3L}{4R} + \frac{3t\left(\frac{L}{R}\right)^2}{8\pi} \right] \tag{2}$$

Among them, the length and diameter of the filler are L and R.

Using a breakdown voltage tester, analyse the breakdown field strength of the specimen, with a boost rate of 0.8 kV/s.

Use a high resistance meter to test the surface and volume resistivity of the specimen, and analyse the current density field strength characteristics; the lower the surface and volume resistivity of the specimen, the better its electrical performance (Ou Yang et al., 2020).

Using two stainless steel needle tip electrodes, analyse the electrical erosion resistance time of the specimen, and the distance between the two electrodes is 7.05 mm. Connect a 15 mA current between the two electrodes to obtain the arc in two stages. The current connection time in the first stage is 50 seconds, with an interval period of one second; the current connection time in the second stage is twice that of the first stage, and the interval period is also one second. Analyse the time required from the carbonisation reaction formed by the arc on the surface of the specimen to the disappearance of the surface arc, namely the resistance to electric erosion time. The longer the resistance to electric erosion time, the better the electrical performance of the specimen (Vovchenko et al., 2023).

Apply pressure on the test piece through the universal testing machine, measure the stress of the test piece with strain gauge, and conduct the electromechanical test combined with the four electrode method.

3 Experimental analysis

3.1 Effect of different amounts of multi-walled carbon nanotubes on the electrical properties of composites

Taking the montmorillonite dosage of 0% and the shear time of 30 minutes as an example, the surface resistivity of the material was analysed at different MWCNT dosages. The analysis results are shown in Figure 2.

According to Figure 2, as the stirring time prolongs, the surface resistivity of the composite material begins to decrease with different MWCNT dosages. The time is short, and the surface resistivity of the composite material decreases faster under all three dosages; when the stirring time is fixed, the more MWCNT is used, the smaller the indicator; when the time is 10 min, the indicator drops to the lowest under all three dosage levels, and the lowest value is around 10^{11} Ω·cm when the dosage is 1%; the minimum surface resistivity at a dosage of 5% is around 10^{10} Ω·cm; the minimum surface resistivity at a dosage of 10% is around 10^{6} Ω·cm. The experimental results show that extending the stirring time and increasing the amount of MWCNT can make the distribution of all raw materials in the composite material more uniform, reduce surface resistivity, and improve conductivity.

Figure 2 Surface resistivity analysis results of composites with different amounts of multi-walled carbon nanotubes

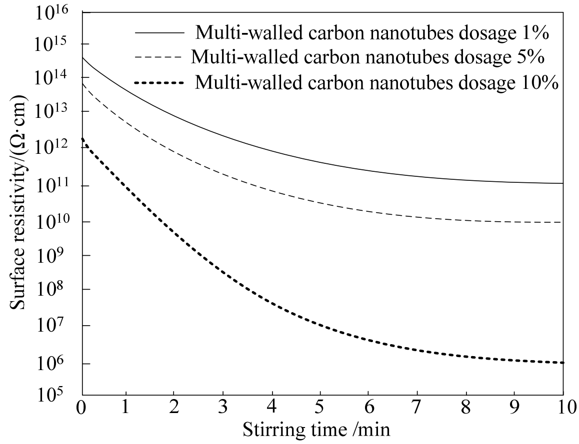
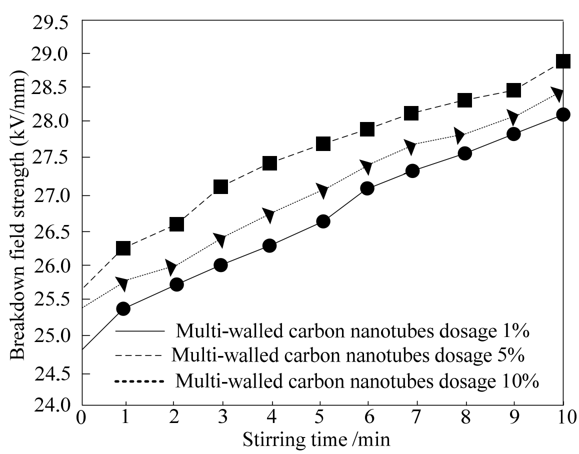


Figure 3 Analysis results of the breakdown field strength

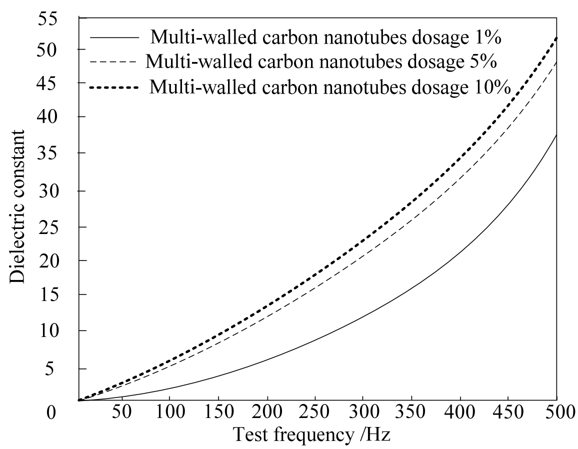


Taking the amount of montmorillonite as 0% and the shear time as 30 min as an example, the breakdown field strength of the material with different amounts of multi-walled carbon nanotubes was analysed, and its value was positively correlated with the electrical properties of the material. The analysis results are shown in Figure 3.

According to Figure 3, as the stirring time prolongs, the breakdown field strength of the three types of multi-walled carbon nanotubes shows an upward trend under different usage levels; as the amount of MWCNT increases, the breakdown field strength of the composite material first increases and then decreases; when the usage of multi-walled carbon nanotubes is 1%, the highest breakdown field strength is around 28.1 kV/mm; when the usage of multi-walled carbon nanotubes is 5%, the highest breakdown field strength is around 28.9 kV/mm; when the usage of multi-walled carbon nanotubes is 5%, the highest breakdown field strength is around 28.5 kV/mm. The experimental results show that an appropriate increase in the amount of multi-walled carbon nanotubes can enhance the breakdown field strength and electrical properties of the composite material. However, the overall improvement in breakdown field strength is relatively small, indicating that the amount of MWCNT has a small impact on the breakdown field strength; when only considering the breakdown field strength of composite materials, the optimal amount of multi-walled carbon nanotubes is 5%.

Taking the amount of montmorillonite as 0%, shear time as 30 min, and stirring time as 10 min, for example, the dielectric constant of the composite material was analysed at different MWCNT amounts, and its value was positively correlated with the material's electrical properties. The analysis results are shown in Figure 4.

Figure 4 Dielectric constant analysis results



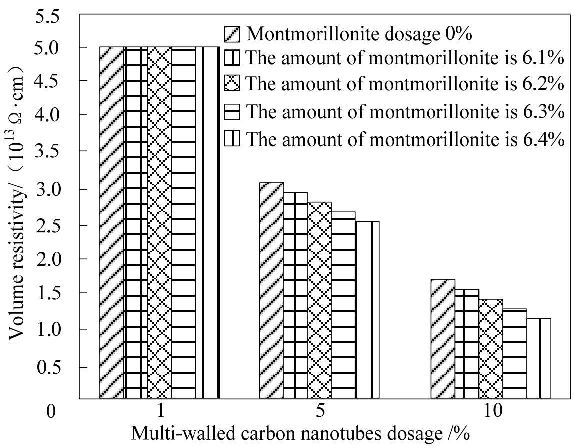
According to Figure 4, for different amounts of multi-walled carbon nanotubes and increasing the testing frequency, the dielectric constant of the composite material can be improved; at a frequency of 500 Hz, the dielectric constant of the composite material reaches its peak at different levels of multi-walled carbon nanotubes. When the usage of multi-walled carbon nanotubes is 1%, the highest dielectric constant is around 38; when the consumption of multi-walled carbon nanotubes is 5%, the highest dielectric constant is around 48; when the usage of multi-walled carbon nanotubes is 10%, the highest dielectric constant is around 52; when the dosage increases from 1% to 5%, the dielectric constant increases rapidly, with an increase value close to 10; when the usage of multi-walled carbon nanotubes increases from 5% to 10%, the increase in the dielectric constant of the composite material is relatively small, with an increase value close to 4. The experimental results show that increasing the amount of multi-walled carbon nanotubes can enhance the dielectric constant of the composite material, that is, improve its electrical properties. When the amount of multi-walled carbon nanotubes increases to

5%, the dielectric constant increases significantly, while when the amount increases to 10%, the dielectric constant increases slightly.

3.2 Influence of different amounts of free soil used on the electrical properties of composite materials

Taking the shear time of 20 min and the stirring time of 10 min as an example, the volume resistivity of the composite material with different amounts of montmorillonite was analysed, and its value had a negative correlation with the conductivity of the material. The analysis results are shown in Figure 5.

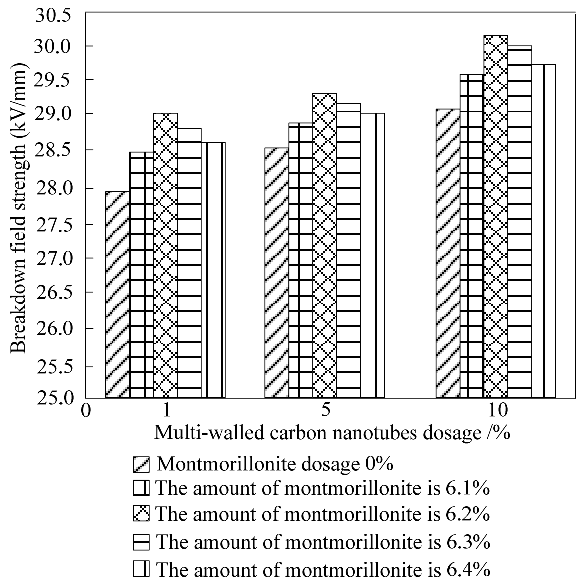
Figure 5 Analysis results of composite volume resistivity with different amounts of montmorillonite



According to Figure 5, when the usage of multi-walled carbon nanotubes is low, adding different amounts of montmorillonite has no effect on the volume resistivity of the composite material; when the amount of multi-walled carbon nanotubes exceeds 5% (including 5%), the increase in the amount of montmorillonite will slightly reduce the volume resistivity of the material; when the amount of multi-walled carbon reaches 10%, the volume resistivity of the composite material decreases to the lowest with different amounts of montmorillonite; when the amount of montmorillonite is 0%, the minimum volume resistivity is around 1.7×10^{13} Ω·cm; when the amount of montmorillonite is 6.1%, the minimum volume resistivity is around 1.5×10^{13} Ω·cm; when the amount of montmorillonite is 6.2%, the minimum volume resistivity is around 1.3×10^{13} Ω·cm; when the amount of montmorillonite is 6.3%, the minimum volume resistivity is around 1.1×10^{13} Ω·cm; when the amount of montmorillonite is 6.4%, the minimum volume resistivity is around. The experimental results show that when the amount of multi-walled carbon nanotubes is less than 5%, the addition of montmorillonite will not affect the volume resistivity of the composite material; when the amount of multi-walled carbon nanotubes exceeds 5% (including 5%), increasing the amount of montmorillonite slightly decreases the volume resistivity, indicating that the addition of montmorillonite has a small impact on the volume resistivity of the composite material, and multi-walled carbon nanotubes themselves have better conductivity.

Taking the shear time of 20 min and the stirring time of 10 min as an example, the breakdown field strength of the composite material was analysed with different amounts of montmorillonite. The analysis results are shown in Figure 6.

Figure 6 Breakdown field strength analysis results of composites with different amounts of montmorillonite

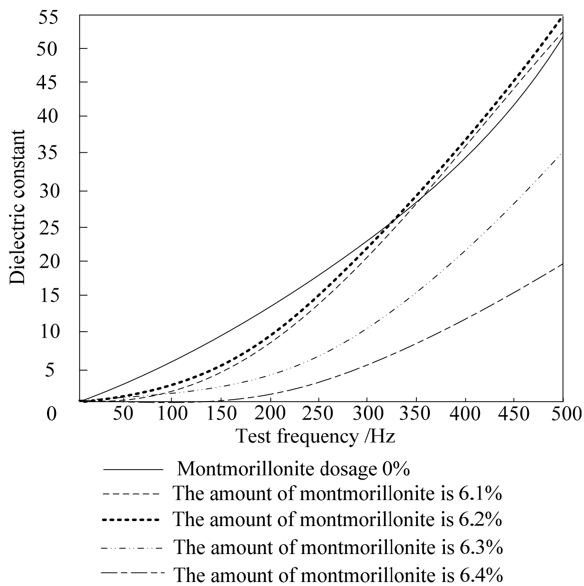


According to Figure 6, for different amounts of multi-walled carbon nanotubes, the addition of montmorillonite will change the breakdown field strength of the composite material; as the amount of montmorillonite increases, the breakdown field strength of the composite material first increases and then decreases; when the amount of montmorillonite is 6.2%, the breakdown field strength of the composite material reaches its peak at various levels of multi-walled carbon nanotubes; when the amount of montmorillonite is 6.2% and the amount of multi-walled carbon nanotubes is 1%, the highest breakdown field strength is around 29.0 kV/mm; when the amount of montmorillonite is 6.2% and the amount of multi-walled carbon nanotubes is 5%, the highest breakdown field strength is around 29.3 kV/mm; when the amount of montmorillonite is 6.2% and the amount of multi-walled carbon nanotubes is 10%, the maximum breakdown field strength is around 30.2 kV/mm. The experimental results show that the appropriate addition of montmorillonite can enhance the breakdown field strength of the composite material, i.e., enhance its electrical properties. Comprehensive analysis shows that the optimal amount of montmorillonite added is 6.2%.

Taking the shear time of 30 min, stirring time of 10 min, and the usage of 10% multi-walled carbon nanotubes as an example, the dielectric constant of the composite material was analysed at different amounts of montmorillonite. The analysis results are shown in Figure 7.

According to Figure 7, as the testing frequency increases, the dielectric constant of the composite material shows an upward trend at different MMT dosages. After adding montmorillonite, the growth rate of the dielectric constant of the composite material is relatively slow when the testing frequency is below 150 Hz; when the dosage of montmorillonite is 6.1% and 6.2%, the dielectric constant of the composite material rapidly increases after the testing frequency exceeds 150 Hz. The maximum dielectric constant at the dosage of 6.2% is higher than the dielectric constant at the dosage of 6.1%. This indicates that when the dosage of montmorillonite is low, increasing the MMT dosage appropriately can improve the dielectric constant. When the amount of montmorillonite is 6.3% and 6.4%, the dielectric constant of the composite material begins to rapidly increase after the testing frequency exceeds 250 Hz, and the dielectric constant at 6.4% is lower than that at 6.3%. This indicates that increasing the amount of MMT can reduce the dielectric constant and improve its insulation performance when the amount of montmorillonite is high. The reason is that increasing the amount of montmorillonite can affect the interfacial force between multi-walled carbon nanotubes and waterborne epoxy resin matrix, reduce the degree of charge aggregation at the interface and inhibit the formation of conductive pathways in multi-walled carbon nanotubes. The experimental results show that when the MMT dosage is small, increasing the MMT dosage appropriately can improve the conductivity of the material; when the MMT dosage is high, increasing the MMT dosage can improve the insulation performance of the material.

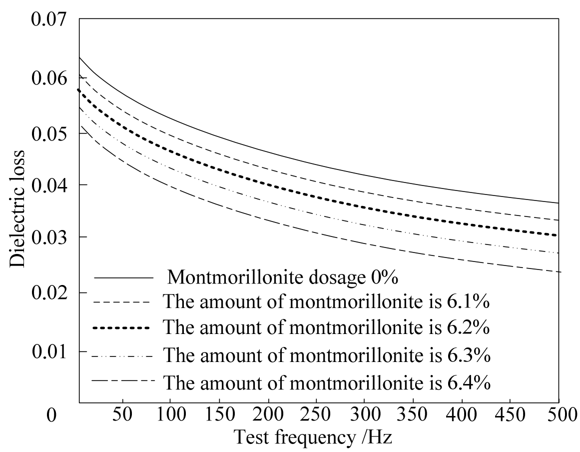
Figure 7 Analysis results of dielectric constant of composites with different amounts of montmorillonite



Taking the shear time of 20 min, stirring time of 10 min, and the usage of 10% multi-walled carbon nanotubes as an example, the dielectric loss of the composite material was analysed with different amounts of montmorillonite. The analysis results are shown in Figure 8.

According to Figure 8, as the testing frequency increases, the dielectric loss of the composite material shows a slight downward trend under different montmorillonite dosages; when the testing frequency is constant, increasing the amount of montmorillonite can slightly reduce the dielectric loss of the composite material; when the amount of montmorillonite is 0%, the minimum dielectric loss is around; when the amount of montmorillonite is 6.1%, the minimum dielectric loss is around; when the amount of montmorillonite is 6.2%, the minimum dielectric loss is around; when the amount of montmorillonite is 6.3%, the minimum dielectric loss is around; when the amount of montmorillonite is 6.4%, the minimum dielectric loss is around. The experimental results show that increasing the amount of MMT does not affect the dielectric loss of the material.

Figure 8 Analysis results of dielectric loss of composites with different amounts of montmorillonite

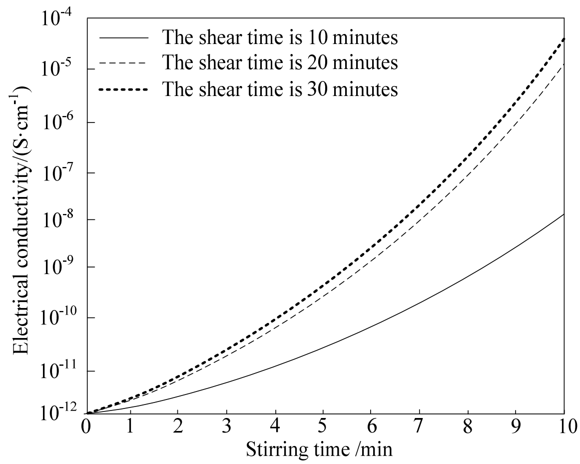


3.3 Effect of different shear times on the electrical properties of the composites

Taking the usage of multi-walled carbon nanotubes at 10%, montmorillonite at 6.2%, and testing frequency at 500 Hz as an example, the conductivity of the material was analysed at different shear times. The value showed a positive correlation with the conductivity of the material. The analysis results are shown in Figure 9.

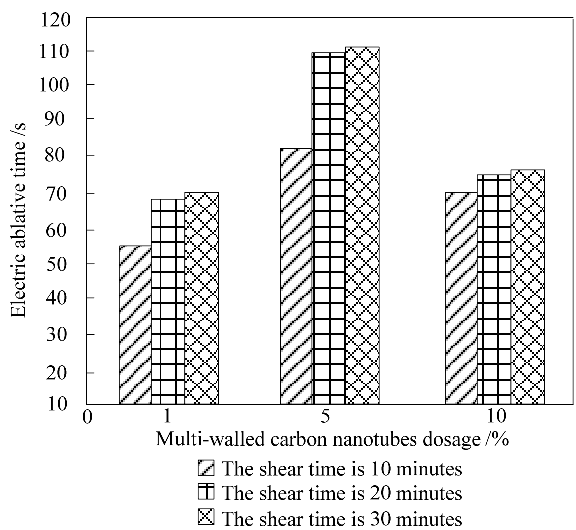
According to Figure 9, it can be seen that extending the stirring time at different shear times can evenly mix all the raw materials in the composite material, improve its conductivity, and thus enhance its conductivity. When the stirring time is fixed, extending the shear time can improve the conductivity of the composite material. When the shear time is increased from 10 min to 20 min, the conductivity of the composite material increases significantly, with the highest conductivity being around 10^{-8} $S \cdot cm^{-1}$ and 10^{-5} $S \cdot cm^{-1}$, respectively; when the shear time is increased from 20 min to 30 min, the conductivity of the composite material slightly increases, with a small increase in amplitude. Comprehensive analysis shows that extending the shear time can improve the dispersion effect of multi-walled carbon nanotubes. The more uniform the distribution of multi-walled carbon nanotubes, the better the conductivity of the composite material; because the increase in conductivity of the composite material is not significant when the shear time is 30 min, considering the energy consumption factor during the preparation process of the composite material, 20 min is the optimal shear time, and the conductivity of the composite material is better at this time.

Figure 9 Analysis results of electrical conductivity of composites at different shear times



Taking the stirring time of 10 min and the amount of montmorillonite at 6.2% as an example, the electrical erosion resistance time of the composite material was analysed at different shear times. The longer the electrical erosion resistance time, the better the electrical performance of the composite material. The analysis results are shown in Figure 10.

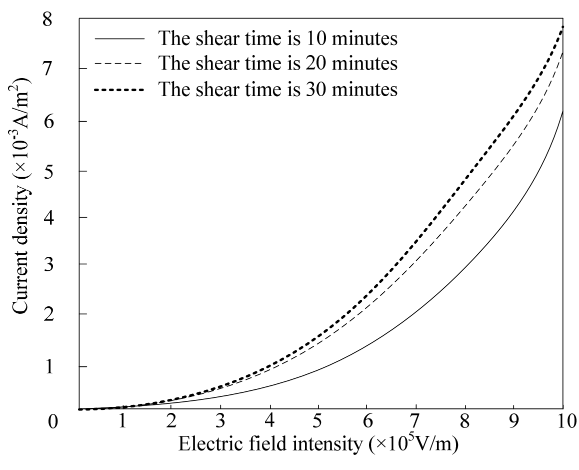
Figure 10 Analysis results of electric ablation time of composites at different shear times



According to Figure 10, it can be seen that when the amount of multi-walled carbon nanotubes is constant, extending the shear time can prolong the electrical erosion resistance time of the composite material. When the amount of multi-walled carbon nanotubes is less than 5% (including 5%) and the shear time is extended, the more the amount of multi-walled carbon nanotubes is used, the greater the improvement in the electrical erosion resistance time of the composite material; when the usage of multi-walled carbon nanotubes is 10%, the electrical erosion resistance time of the composite material begins to shorten at different shear times. When the amount of multi-walled carbon nanotubes is different, the increase in electrical erosion resistance time of the composite material is significant when the shear time is increased from 10 min to 20 min. However, when the shear time is increased from 20 min to 30 min, the increase in electrical erosion resistance time of the composite material is relatively small. The experimental results show that when the amount of multi-walled carbon nanotubes is less than 5% (including 5%), prolonging the shear time can quickly increase the electrical erosion resistance of the composite material. When the amount of multi-walled carbon nanotubes is 10%, prolonging the shear time can slow down the electrical erosion resistance of the composite material. Extending the shear time can extend the electrical erosion resistance of the material. By increasing the amount of multi-walled carbon nanotubes, the electrical erosion resistance time of the composite material is first extended and then shortened.

Taking the stirring time of 10 min, the amount of multi-walled carbon nanotubes used at 10%, and the amount of montmorillonite used at 6.2% as an example, the relationship between current density and field strength of the composite material at different shear times was analysed. The analysis results are shown in Figure 11.

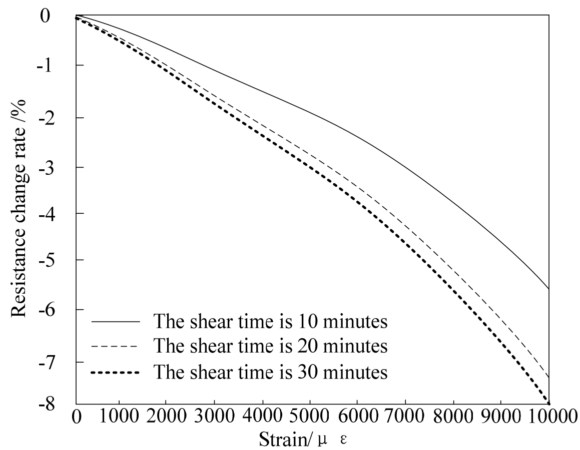
Figure 11 Relation curves of current density-field intensity of composites at different shear times



According to Figure 11, it can be seen that under different shear times, the current density and electric field strength of the composite material show a monotonically increasing relationship. When the electric field intensity is below 2×10^5 V/m, the increase in current density of the composite material was not significant under the three shear times; when the electric field strength exceeds 3×10^5 V/m, the current density of the composite material rapidly increases under all three shear times. Among them, when the shear time is 20 min, the increase in current density is the largest, while when the shear time is 30 min, the increase in current density is not significant. The experimental results indicate that extending the shear time will reduce the resistance of the composite material, rapidly increase its current density, and thus enhance its conductivity.

Taking the stirring time of 10 min, the amount of multi-walled carbon nanotubes used as 10%, and the amount of montmorillonite used as 6.2% as an example, the mechanical and electrical properties of the composite material were analysed at different shear times. The analysis results are shown in Figure 12.

Figure 12 Analysis results of mechanical and electrical properties of composites at different shear times



According to Figure 12, it can be seen that the mechanical and electrical changes of the composite material are completely the same at different shear times, and the rate of resistance change decreases with the increase of strain. When the shear time increases from 10 min to 20 min, the decrease in resistance change rate is significant; when the shear time is increased from 20 min to 30 min, the rate of resistance change remains basically unchanged. The experimental results show that extending the shear time can make the distribution of multi-walled carbon nanotubes more uniform, and the corresponding distribution of waterborne epoxy gaps is also more uniform and less discrete, accelerating the rate of decrease in resistance change and improving its mechanical and electrical properties.

4 Conclusions

Waterborne epoxy resin carbon nanotube composites have advantages such as excellent curing and conductivity, and are well applied in various fields. In order to further improve the electrical properties of the composites, waterborne epoxy resin carbon nanotube composites are prepared with waterborne epoxy resin and montmorillonite as raw materials, and their electrical properties are analysed. The experimental results show that an appropriate increase in the amount of multi-walled carbon nanotubes can enhance the breakdown field strength of the composite material, that is, improve its electrical properties. However, the overall breakdown field strength improvement is relatively small, indicating that the amount of MWCNT does not affect the breakdown field strength of the material; increasing the amount of MWCNT can improve the dielectric constant of the material, which means improving its electrical properties. When the amount of multi-walled carbon nanotubes increases to 5%, the dielectric constant increases significantly, reaching around 48; when the dosage increases to 10%, the increase in dielectric constant is relatively small, reaching around 52; increasing the amount of MMT will not affect the dielectric loss of the material; extending the shear time can make the distribution of multi-walled carbon nanotubes more uniform, and the corresponding waterborne epoxy gap distribution is also more uniform and less discrete, improving the decrease in resistance change rate and enhancing its mechanical and electrical properties.

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