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Controllable Preparation and Electrically Enhanced Particle Filtration Performance of Reduced Graphene Oxide Polyester Fiber Materials in Public Buildings

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Abstract: How to effectively improve the filtration characteristics of polyester fiber filtration materials in public buildings is particularly important for ensuring the health of indoor environments. This study uses the impregnation method to prepare composite materials by using the characteristics of graphene and its derivatives and, on this basis, enhances the filtration characteristics of the composite materials by applying an external voltage. The structure and particle filtration performance of the composite materials are tested and analyzed. The results indicate that the filtration efficiency of the prepared composite filter material is significantly improved compared to polyester fiber materials. When the applied voltage is 4 V, the new composite filter material has the highest weight filtration efficiency for particulate matter, with filtration efficiencies of 71.3%, 45.3%, and 35.7% for PM_{10}, $PM_{2.5}$, and $PM_{1.0}$, respectively. The filtration efficiency is highest when the power on time is 80 s. At this time, the filtration efficiency of the filter material for PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ is 70.6%, 43.8%, and 35.3%, respectively. The new composite filter material has a significant lifting effect on particles with a diameter of 0–2.5 μm. It provides reference value for research and the application of new filtering materials.

Keywords: polyester; compound material; power up; particulate matter; filtration performance

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1. Introduction

Knowing how to avoid a series of problems caused by air pollution has always been a key and difficult point for researchers and research institutions [1–3]. This is because the air contains not only particulate matter and harmful gases but also a large number of microorganisms [4]. However, due to changes in the environment, its concentration and physical and chemical properties change. When people live and are exposed to such an environment, it can easily cause various physical and mental problems [5–8], such as respiratory diseases [5], cardiovascular diseases [6], depression [7], and even death [8]. According to the relevant literature, 80% of a person's life is spent indoors [9], so the quality of the indoor environment is particularly important for people's lives, and it can be especially deadly for the elderly and children with weak immunity levels [10]. Learning how to ensure indoor health has become a goal pursued by many people.

As is well known, air filters can effectively convert outdoor polluted air into clean air through fiber filtration and send it indoors, thus gaining widespread application [11]. At present, a large number of scholars at home and abroad have conducted extensive research on air filters [12–17] using Computational Fluid Dynamics (CFD) simulation [12], experimental testing [13], and theoretical formula derivation [14] as well as a combination of simulation testing [15], theoretical formula testing [16], simulation theoretical formulas [17], and other methods to conduct performance testing research on filters. At present, the focus of the relevant research is also on improving the high efficiency and low resistance performance of filters [18], filter combination performance [19], filter temperature and humidity performance [20], filter sterilization [21], and the filter usage environment [22]. Although certain research results have been obtained and applied in the market, there are still practical problems, such as low efficiency and high resistance. In the post-pandemic era, the actual demand for filters to meet the higher demand, more frequent replacement frequency, and higher filtration performance requirements has brought enormous challenges.

Therefore, the development and application of new composite materials have been favored by various industries, especially in the field of ventilation and purification [23]. At present, the processes of material synthesis and preparation are relatively mature. However, due to cost issues, difficulty in preparation processes, and differences in actual effects, new composite materials have not been widely promoted and are mostly based on laboratory test results [24]. Therefore, traditional filter materials are still used today. However, composite materials formed by combining traditional materials with porous materials have been widely used, among which polyester fiber materials are relatively more commonly used. This is because polyester fiber materials are still the most commonly used, widespread, and economical filtering materials in large public buildings [25], and they are also the main force in synthetic fibers, occupying a pivotal position in the textile field. The most commonly used porous materials are currently graphene and its derivatives [26]. Graphene and its derivatives have been widely used in air treatment due to the characteristics they have displayed since their inception. By utilizing their characteristics, such as a large specific surface area and conductivity, research has been conducted on capacitors, masks, and other related materials [27,28], and positive results have been achieved. Although there have been studies combining graphene and its derivatives with polyester fiber materials, non-woven fabric materials, etc., more research has been conducted on their structural properties and stability. There is almost no research on whether polyester fibers attached with graphene and its derivatives can have electrical conductivity, whether the filtering performance changes after electrical conductivity, and the optimization of electrical parameters. In addition, the filtration process in traditional filter materials mainly relies on the diffusion effect, interception effect, and inertia effect to effectively capture particulate matter [29]. There is relatively little research on the removal of fine particulate matter and other pollutants from the air using polyester fiber materials with electrically enhanced filtration. Therefore, there is a serious lack of research on the filtration performance of reduced graphene oxide polyester fiber materials prepared by the impregnation method and their electrically enhanced particulate matter.

Based on the above practical situation, this study uses the impregnation method to prepare the composite materials of commonly used polyester fiber filter materials in the market by utilizing the characteristics of graphene and its derivatives. On this basis, the filtration characteristics of the composite materials are enhanced by an external voltage, and their structure and particle filtration performance are tested and analyzed. This study can provide reference value for the research and development of new fiber filtration materials, and it has immeasurable significance for promoting the upgrading and replacement of

the polyester fiber industry, expanding its application fields, and meeting the demand of society for high-performance materials.

2. Methods

2.1. Material and Equipment

The polyester fiber material was produced by Guangdong Fresh Filter Co., Ltd., Foshan, China, with the grade of G4, EN779 [30], and ISO9001 [31]. The oxidized graphene material was produced by Suzhou Tan Feng Graphene Technology Co., Ltd., Suzhou, China, with a purity of 0.95. The reducing agent used was L-ascorbic acid, produced by Tianjin Kemio Chemical Reagent Co., Ltd., Tianjin, China, and analyzed as pure AR. The deionized water was produced by Hangzhou Yongjieda Purification Technology Co., Ltd., Hangzhou, China, with a pure water machine.

The magnetic stirrer was supplied by Guangzhou Yike Laboratory Technology Co., Ltd., Guangzhou, China; the electric hot blast constant temperature box was supplied by Shangcheng Instrument Manufacturing Co., Ltd., Hangzhou, China; the CNC ultrasonic cleaner was supplied by Kunshan Ultrasonic Instrument Co., Ltd., Kunshan City, China; the scanning electron microscope was supplied by Japan Electronics Corporation, Osaka, Japan; the thermostatic water bath was supplied by Shanghai Lichen Bangxi Instrument Technology Co., Ltd., Shanghai, China; the digital multimeter was supplied by Ulide Technology (China) Co., Ltd., Beijing, China; the GRIMM1.109 portable aerosol particle size spectrometer was supplied by Beijing Saak-Mar Environmental Instrument Co., Ltd., Beijing, China. The HD2114P. 0 differential pressure gauge was supplied by DeltaOHM, Torino, Italy; the HD37AB1347 indoor air quality monitor was supplied by DeltaOHM Co., Ltd., Italy; the external power supply was supplied by Nanfu Battery, Nanping, China. The GRIMM1.109 portable aerosol spectrometer is used to measure the particulate matter concentration before and after the use of air filters. The HD2114P. 0 differential pressure gauge is used to test the filter resistance. The HD37AB1347 indoor air quality detector is used to measure the velocity inside the pipeline. The scanning electron microscope is used to scan the near fiber structure. The average concentration values of the test filter before and after 5 min are used as the calculated values to reduce experimental errors.

2.2. Preparation of Reduced Graphene Oxide Polyester Fiber Material

Take 4 pieces of polyester fiber material of the same size, with a size of 7 × 7 cm, fully immerse them in deionized water, dry them at 70 °C for 40 min, and set them aside. Among them, 2 pieces are the blank control group, numbered A, and 2 pieces are used to prepare the reduced graphene oxide polyester fiber material, numbered B. Prepare a dispersion solution by mixing the graphene oxide material with deionized water in a certain ratio to obtain a 4.0 g/L solution, followed by sonication for 1 h. Fully immerse the 2 pieces of material into the graphene oxide solution, heat them in a water bath for 60 min at a set temperature of 60 °C, and then dry them at 70 °C for 60 min to obtain 2 pieces of graphene oxide filter material. Prepare a 0.2 mol/L reducing agent solution with deionized water, completely immerse the 2 pieces of graphene oxide filter material into the reducing solution, heat them in a water bath according to the set time and temperature, and dry them after a certain period of time to obtain 2 pieces of reduced graphene oxide polyester fiber material.

To ensure the uniformity and accuracy of the materials, 2 pieces of material under the same conditions are simultaneously used as test samples each time. For the testing of the filtration performance, each group is tested twice for the different speed parameters of the filter material, with a total of 10 tests for 5 variables and 2 pieces per group, for a total of 20 tests. Two sets of materials are tested a total of 40 times, and to ensure the accuracy of the results, the average of the 2 results is used for the analysis in each test. In addition, the

new reduced graphene oxide filter material is connected to an adjustable power supply. Its voltage level (0 V, 2 V, 4 V, 6 V, 8 V) and power on time (0 s, 40 s, 80 s, 120 s, 160 s) are changed for the performance testing. There are a total of 2 blocks in Group B, each of which undergoes 2 tests for power on voltage and power on time, with a total of 20 tests for 10 variables under 2 parameters. The 2 blocks in Group B undergo a total of 40 tests. Taking the average of the 2 tests for the analysis ensures the validity of the test results and the authenticity of the data.

2.3. Performance Formula

The air filter filtration efficiency was calculated using Equation (1) [32].

$$\eta = \frac{C_1 - C_2}{C_1} \times 100\% \quad (1)$$

where η is the filtration efficiency (%); C_1 is the concentration of particulate matter before filtration ($\mu g/m^3$); and C_2 is the concentration of particulate matter after filtration ($\mu g/m^3$).

The air filter counting efficiency was calculated using Equation (2) [32].

$$\eta_i = (1 - \frac{N_{2i}}{N_{1i}}) \times 100\% \quad (2)$$

where η_i is the counting efficiency (%); N_{1i} is the average counting concentration of a certain particle size in a segment before filtration (particle/L); and N_{2i} is the average counting concentration of a certain particle size in a segment after filtration (particle/L).

The filtration velocity was the same before and after the filters were applied, and the cross-sectional area was equal. The filtration resistance could be expressed as the static pressure difference and was calculated using Equation (3) [32].

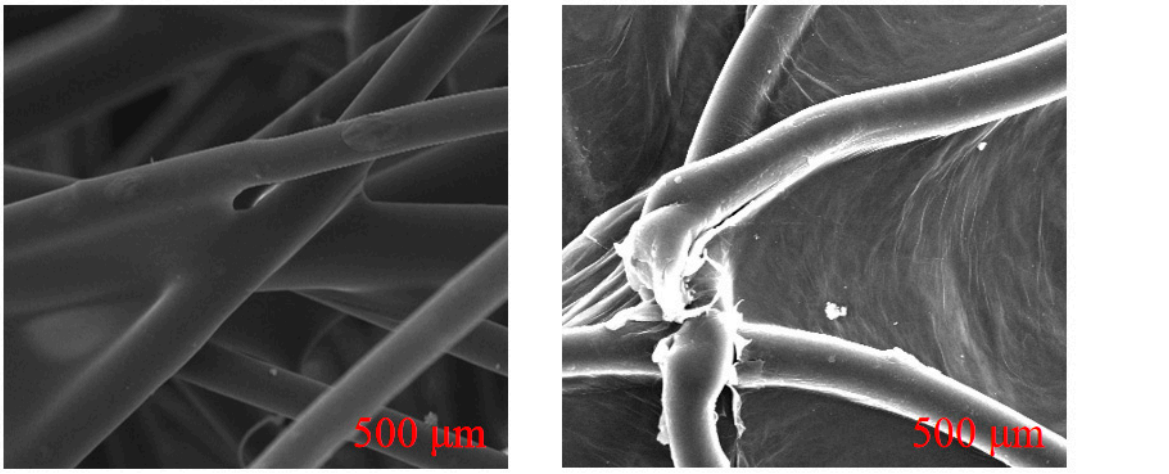
$$\Delta P = P_2 - P_1 \quad (3)$$

where P_1, P_2 is the static pressure before and after filtration (Pa).

3. Results and Discussion

3.1. Appearance Analysis of Reduced Graphene Oxide Polyester Fiber Material

The electron microscope scanning images of the two types of filter materials are shown in Figure 1.



(**A**) Polyester fiber material (**B**) Reduced graphene oxide polyester fiber material

Figure 1. Electron microscopy scanning image of filter material.

From Figure 1, it can be seen that the original polyester fiber air filter material, which is marked A, exhibits a natural tendency toward flatness and smoothness, and the fibers are naturally arranged. The surface of each fiber in the reduced graphene oxide polyester fiber material, which is marked B, becomes relatively rough, and its surface structure undergoes significant changes. A partial encapsulation layer appeared on the surface of the fibers, accompanied by some cross-linking and wrinkling, with a small portion exhibiting particle accumulation. This result is consistent with the literature findings and verifies the correctness of the results presented in this paper [33]. Furthermore, it is evident that the porosity of the fibers has decreased, resulting in higher filtration efficiency under the same conditions. Overall, it can be clearly seen that the internal structure of the synthesized composite material has changed, making its fiber structure more stable.

3.2. Influence of Filtration Velocity

Atmospheric dust was used as the dust source for testing [34]; the trend of the filtration efficiency of the two different materials as a function of the filtration velocity is shown in Figure 2.

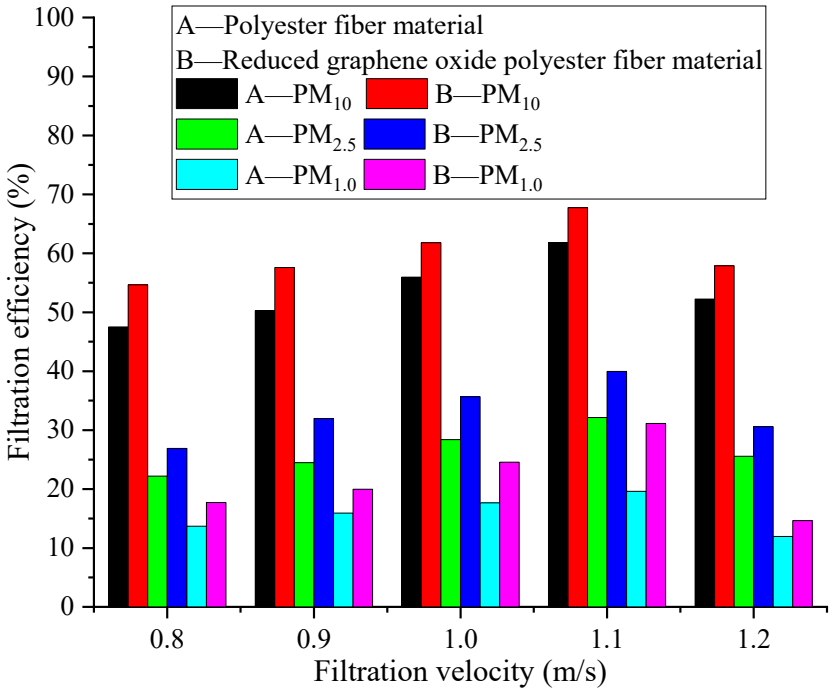


Figure 2. Filtration efficiency varied with filtration velocity.

From Figure 2, it can be seen that as the filtration velocity increases, the filtration efficiency of both of the materials shows a trend of first increasing and then decreasing. At this point, the inertia effect and interception effect increase, while the diffusion effect decreases, increasing the capture efficiency of the particulate matter [35]. Small particles are mainly affected by Brownian diffusion, so the capture effect of small particles is lower than that of large particles. The reduced graphene oxide polyester fiber material, which is marked B, has increased the filtration efficiency of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ by 5.6~7.3%, 4.7~7.8%, and 2.7~11.5%, respectively. This is because the composite filter material, which is marked B, has changed the internal structure of the original fibers, making them denser and reducing the porosity. Under the same conditions, when dusty airflow passes through, the denser fiber structure will increase the probability of particle capture, resulting in a significant improvement in filtration efficiency. However, at a filtration velocity of 1.1 m/s, the filtration efficiency of both filter materials reaches its maximum.

3.3. Influence of Voltage Magnitude

To further investigate the effect of voltage magnitude on the reduced graphene oxide polyester fiber material, which is marked B, the voltage magnitude was selected for experimentation at an optimal velocity of 1.1 m/s. The impact of different voltage magnitudes on the weight filtration efficiency of the new composite filter material is shown in Figure 3.

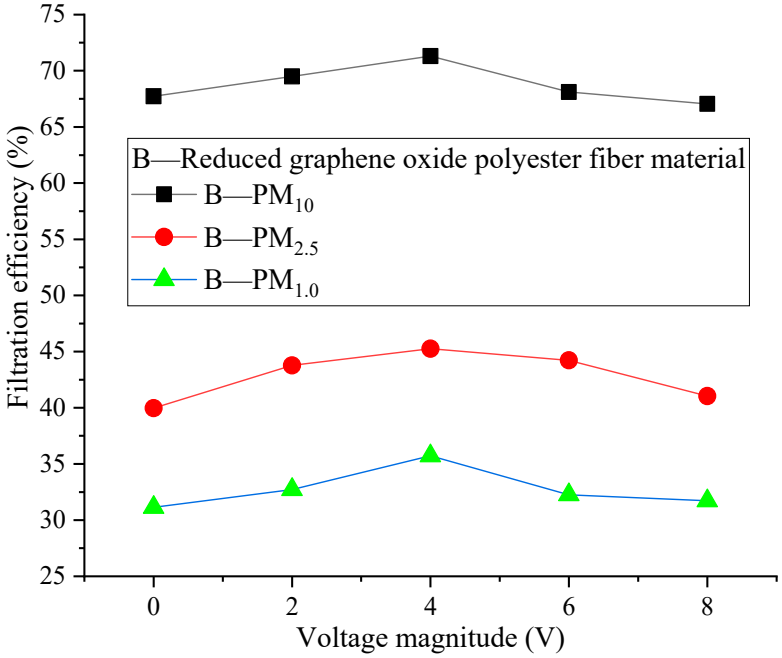


Figure 3. Filtration efficiency varied with voltage magnitudes.

From Figure 3, it can be seen that the filtration efficiency of the reduced graphene oxide polyester fiber material, which is marked B, is significantly improved compared to the absence of voltage after applying a voltage of 2 V. This is because, after applying the voltage, the surface fiber resistivity varies, which results in different current densities on the fibers and the phenomenon of space charge accumulation. At this point, in addition to mechanical filtration, there is also an electrostatic effect of surface space charge on the particles in the airflow. This result is consistent with the literature results, verifying the correctness of the results in this paper [36]. Therefore, after applying the voltage to the reduced graphene oxide polyester fiber material, which is marked B, the filtration efficiency is improved. When a voltage of 4 V is applied, the current increases, and the current density also increases, resulting in an increase in the number of space charges and an increase in the electrostatic effect on particles in the airflow. At this time, the reduced graphene oxide polyester fiber material, which is marked B, has the highest weight filtration efficiency for particles, with a filtration efficiency of 71.3% for PM_{10}, 45.3% for $PM_{2.5}$, and up to 35.7% for $PM_{1.0}$. When the applied voltage is 6–8 V, the filtration efficiency decreases. This is because, as the voltage increases, the surface temperature of the filter material also increases, leading to an accelerated dissipation rate of space charges on the surface of the filter material and a decrease in the electrostatic interactions. Therefore, it can be seen that the optimal applied voltage is 4 V.

3.4. Influence of Power on Time

Under the same conditions and with a voltage of 4 V, the effect of different energization times on the filtration efficiency of the reduced graphene oxide polyester fiber material, which is marked B, is shown in Figure 4.

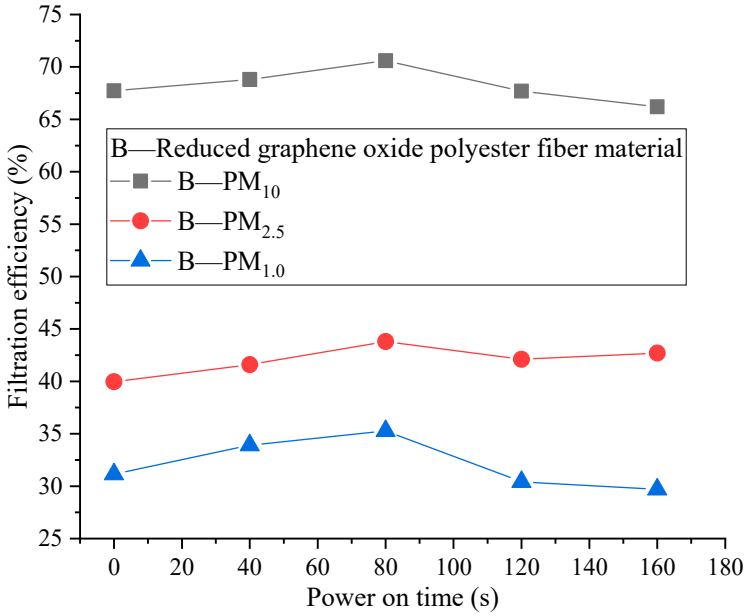


Figure 4. Filtration efficiency varied with power on time.

From Figure 4, it can be seen that as the electrification time changes, the filtration efficiency of the reduced graphene oxide polyester fiber material, which is marked B, for the particulate matter shows a trend of first increasing and then decreasing. When the power on time is 80 s, the reduced graphene oxide polyester fiber material, which is marked B, has the best filtration effect on PM_{10}, $PM_{2.5}$, and $PM_{1.0}$, with filtration rates of 70.6%, 43.8%, and 35.3%, respectively. When the power on time is 80–160 s, the filtration efficiency of the particulate matter decreases. This is because, the longer the power on time, the less the graphene oxide polyester fiber material (which is marked B) generates heat, causing a certain structural deformation of its surface fibers. Therefore, it can be seen that 80 s is the optimal power on time.

3.5. Influence of Voltage and Power on Time on Counting Filtration Efficiency

Under the optimal voltage of 4 V and 80 s, the counting filtration efficiency of the two materials is shown in Figure 5.

From Figure 5, it can be seen that the counting filtration efficiency of the reduced graphene oxide polyester fiber material is significantly higher than that of the polyester fiber material without external electrical conditions under the condition of a voltage of 4 V and an electrical duration of 80 s. This is because, in the absence of an external voltage, Brownian motion dominates, and small particles will bypass the fibers with the airflow without being captured by the fibers [35]. The new composite filter material treated with an external voltage generates a certain amount of charge, which captures small particles in the airflow through the fiber surface due to electrostatic effects, thereby improving its filtration efficiency. It can be clearly seen from the figure that there is a significant difference between the two materials in filtering particles from 0 to 2.5 μm. The new composite filter material has a more obvious effect, with a maximum difference of 17.3%. The difference in particles larger than 2.5 μm becomes smaller and smaller because the larger the particle size, the stronger its inertia effect, resulting in a higher probability of being captured by fibers.

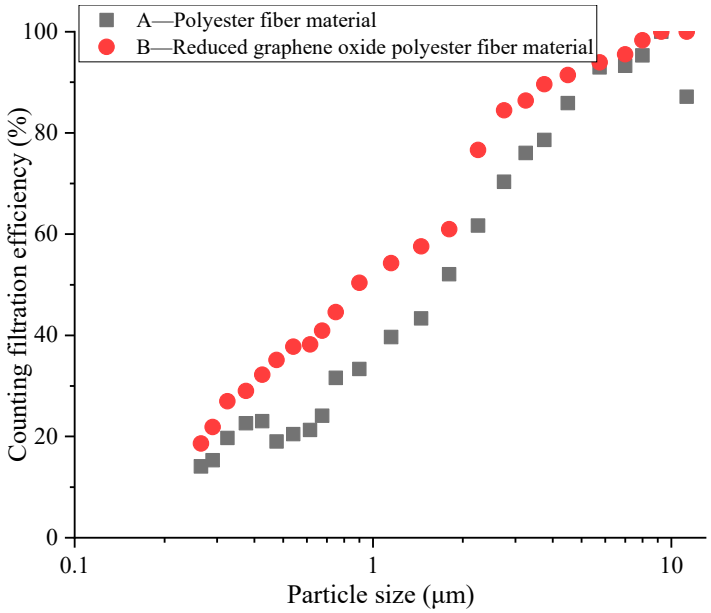


Figure 5. Counting filtration efficiency of two materials.

3.6. Influence of Voltage and Power on Time on Filtration Resistance

The changes in the filtration resistance of the reduced graphene oxide polyester fiber material, which is marked B, under different voltages and energization times are shown in Table 1.

Table 1. Changes in filtration resistance of reduced graphene oxide polyester fiber filter.

Type	Different Voltage Magnitudes (V)					Different Power on Time (s)				
	0	**2**	**4**	**6**	**8**	**0**	**40**	**80**	**120**	**160**
Filtration resistance (Pa)	48.5	50.5	49	51	50.5	48	46.5	47	49.5	50.5
Average (Pa)			49.9					48.3		

From Table 1, it can be seen that regardless of changing the voltage or the duration of power on, the filtration resistance of this new composite filter material changes relatively little, with a variation amplitude of less than 5.0%. This is because the filtering resistance mainly comes from the drag force of the filtering fibers on the airflow [37], and the accumulation of particles between the fibers increases the drag force of the fibers on the airflow, resulting in an increase in resistance. Applying an external voltage to the new composite filter material can effectively reduce the accumulation of particles between fibers. Therefore, the new composite filter material can achieve the effect of improving the filtration efficiency and maintaining stable filtration resistance by applying an external voltage. The changes in the filtration resistances of the two materials at the different filtration velocities are shown in Figure 6.

From Figure 6, it can be seen that the filtration resistance of both of the materials increases with the increase in the filtration velocity. Within the filtration velocity range, the resistance range of the polyester fiber material, which is marked A, is 29.5–47.5 Pa. The resistance range of the reduced graphene oxide polyester fiber material, which is marked B, is 35.5–53 Pa. It can be seen that the resistance of the reduced graphene oxide polyester fiber material is slightly higher than that of the polyester fiber material, with an overall increase of 5–7 Pa. The reduced graphene oxide polyester fiber material, after being treated with graphene, and the changes in internal gaps and intervals are confirmed by the fiber structure in Figure 1. Therefore, under the same conditions, the resistance of dusty

gas passing through the fiber increases, affecting the uniformity of the airflow velocity field. This is consistent with the conclusions found in the literature [38]. This is related to the structure of the fibers, which also indicates that in practical use, the two evaluation indicators of resistance and filtration efficiency need to be selected according to the actual usage location. With the continuous rise of underground engineering, using new composite materials to ensure the stability and safety of underground special environments will be another research hotspot in the future, which requires continuous in-depth research on composite materials from multiple perspectives [39–43].

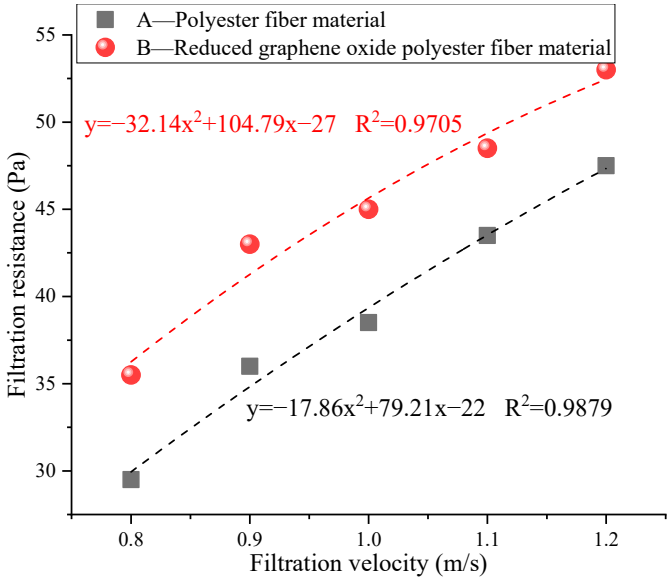


Figure 6. Filtration resistance of two materials.

4. Conclusions

The characteristics of graphene and its derivatives in the preparation of composite materials of polyester fiber materials commonly used in public buildings by impregnation were studied in this paper, which tested and analyzed the structure and particle filtration performance of the composite materials by applying an external voltage. The following conclusions were preliminarily made:

1. The prepared reduced graphene oxide polyester fiber material improved the filtration efficiency of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ by 5.6% to 7.3%, 4.7% to 7.8%, and 2.7% to 11.5%, respectively.
2. The applied voltage was 4 V, and the new composite filter material had the highest weight filtration efficiency for the particulate matter, with filtration efficiencies of 71.3%, 45.3%, and 35.7% for PM_{10}, $PM_{2.5}$, and $PM_{1.0}$.
3. The filtration efficiency was the highest when the power on time was 80 s. At this time, the filtration efficiency of the filter material for PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ was 70.6%, 43.8%, and 35.3%.
4. The new composite filter material had a significant lifting effect on particles with a diameter of 0–2.5 μm. It provides reference value for the research and application of new filtering materials.

Especially on the basis of the electrification performance of the filter material, future research can focus on the disinfection and sterilization of microorganisms in the air. After electrification, the temperature of the fiber surface will rise, reducing the environment in which microorganisms grow and live in large numbers due to the humidity of the fiber, thus reducing the number of microorganisms entering the room with the air supply. This will be

the focus of future material research—as well as the subsequent expansion of this work—on the power on condition of filter materials under the condition of microbial disinfection and sterilization, and the parameter optimization under the synergetic effect of particles.

Author Contributions: Conceptualization, X.S. and T.Y. (Tuo Yang); methodology, X.Z.; investigation, X.S. and X.Z.; data curation, T.Y. (Tao Yu); writing—original draft preparation, X.Z. and T.Y. (Tuo Yang); writing—review and editing, X.Z. and T.Y. (Tao Yu). All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: Authors Xiaolei Sheng and Tuo Yang were employed by the Shaanxi Dijian Real Estate Development Group Co., Ltd., and Tianjin Chengjian University Architectural Design and Research Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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