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The Efficiency of Functional Activated Carbon Non-woven Fabric Filters for Fine Dust Reduction

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Abstract

Particulate matter (PM) concentrations are significantly higher in urban railway tunnels (178.1 μg/m^3) than in metropolitan areas (49 μg/m^3). Nitrogen oxide (NOx) concentrations, which are a direct cause of lung disease, have been found to exceed the atmospheric standard of the Ministry of Environment in tunnels in Korea. Dust generated by trains is scattered at high speed along tunnels, making filtration difficult. The development of filters that can be used in tunnels is urgently required. In this study, the results of using an activated carbon filter (ACF) were analyzed and compared with the laboratory-scale PM adsorption using functional activated carbon non-woven fabric filters (Cerebasel, Cerecore) that can be manufactured in Korea. The fine PM concentration, filter depth, and flow rate in the tunnel were the experimental variables. We compared PM concentrations before and after the filter experiments, and calculated the PM removal efficiency to determine the optimal conditions. A comprehensive examination of the experimental variables and differential pressure showed that the optimal conditions for the Cerecore filters were a wind speed of 3.0 m/s and pressure of 600 mm. The Cerecore filter removal efficiency was 53.5% for PM_{10} and 40.3% for $PM_{2.5}$. Although the PM removal efficiency was relatively low in indoor and outdoor tests, the results indicated a potential applicability, with the filters having various advantages over alternative particle removal methods. Reproducibility tests showed that the functional activated carbon non-woven fabric filters could be washed and reused, and their ease of maintenance made them suitable for various settings.

Keywords: Fine Particulate Matter; Activated Carbon Non-Woven Fabric; Optimal Removal Efficiency; Cerebasel; Cerecore

Introduction

There is much public interest in particulate matter (PM), with particular concern focused on fine PM pollution. Fine dust is a major air pollutant caused by natural and human activities, and it affects air quality, climate, and human health [1-5]. Numerous studies have revealed the effects of exposure to fine dust on respiratory diseases, heart failure, and mortality. In particular, mortality after exposure to $PM_{2.5}$ was found to be higher than that after exposure to PM_{10} [6].

Subway systems can be heavily contaminated with fine dust, and users have a high level of concern regarding the railway environment. These spaces therefore require intensive management. Fine dust is generated in subway systems by friction and abrasion between rails and wheels, pantographs, and power supply facilities while the train is running, and it can also accumulate on the floor due to rail grinding and the maintenance of underground structures. Dispersion by the airflow caused by passing trains is the main mechanism of PM resuspension. The fine dust concentration in urban railway tunnels (178.1 ug/ m^3) has been reported to be much higher than that in surrounding metropolitan areas (49 ug/ m^3) [7]. Nitrogen oxide (NOx) concentrations, which are a direct cause of lung disease, have been found to exceed the atmospheric standard of the Ministry of Environment in subway tunnels, and PM concentrations have also been reported to be very high. Fine dust generated by trains is scattered at high wind speeds and is difficult to filter. It is therefore necessary to develop a non-motorized filter that is easy to maintain in a tunnel environment [1].

Porous materials are used as adsorbents to remove environmentally harmful substances, with activated carbon being a representative example that is widely applied in water purification, food manufacturing, and solvent recovery. However, activated carbon has a long adsorption time and a high dust generation rate and, therefore, secondary pollution may occur [1]. In addition, the wide pore size distribution of activated carbon limits the removal of trace pollutants by adsorption and the selective adsorption capacity of the mixture. As a result of a comparative analysis of heavy metal adsorption properties in previous studies, it was confirmed that an activated carbon filter (ACF) had a higher adsorption capacity than granular activated carbon (GAC) [1].

An ACF has a diameter of 10 μm or less, and has a uniform distribution of micropores (10–20 Å) in a fiber yarn with a specific surface area of 1,200–3,000 m^2/g [1,8]. An ACF has 1.5–10 times greater adsorption capacity and a 100–1,000 times faster adsorption rat e than GAC. In addition, the pressure loss is 1/4–1/10 that of GAC, enabling the removal and separation of trace substances [1,8]. In addition, it can be applied in various locations because it is easy to commercialize as a non-woven fabric due to its lightness, flexibility, and malleability [9-11]. Unlike GAC, the performance of an ACF does not depend on the internal diffusion resistance and, therefore, the adsorption device can be miniaturized and desorption is easy. It therefore exhibits excellent regeneration characteristics. Therefore, ACF is very useful as an adsorbent in various applications requiring precise separation, such as waste water treatment, air purification, and harmful gas filtration. However, the operation of an ACF is completely dependent on foreign imports. Therefore, the purpose of this study was to analyze and compare the adsorption performance of an existing ACF with domestic products that were laminated by the processing of activated carbon and carbon layer materials.

The Japan Electric Power Research Institute installed a fence alongside a roadside that incorporated an ACF to remove NO_X from automobile exhaust that was disseminated by wind flows around arterial roads [12-14]. The Korea Railroad Research Institute developed a functional ACF filter that simultaneously removes fine dust and harmful microorganisms by laminating copper particles and an ACF [15]. However, there have been few studies that have determined the efficiency of fine dust reduction using such ACF systems.

The purpose of this study was to improve the efficiency of ultra-fine dust reduction in subway stations and tunnels, based on the fine dust removal efficiency of non-powered functional activated carbon non-woven fabric filters. The filters were analyzed to examine their removal efficiency. In this study, after the laboratory results were obtained, an additional review was performed to determine their applicability in indoor and outdoor spaces. The applicability and optimal conditions for the operation of domestically produced filters in subway tunnels and stations were derived.

Materials and methods

Experimental subject and period

In this study, the adsorption performance of functional activated carbon non-woven fabric filters at the laboratory scale was investigated, and its applicability in indoor and outdoor environments was investigated. In this experiment, in addition to the existing ACF filters (Beihai Fiberglass Co., Ltd., Jiujiang, China), which are supplied entirely as foreign imports, two functional activated carbon non-woven fabric filters manufactured in Korea (Cerebasel, Cerecore) were also assessed. The PM_{10} and $PM_{2.5}$ removal efficiencies were analyzed and compared. Experiments were conducted on a laboratory scale from November to December 2020. In addition, it was performed in December 2020 following an installation in front of the back door of Yakdae Elementary School in Bucheon City. This system achieved fine dust removal based on the fence-type filters that have been used in outdoor spaces. The efficiency in actual field situations was then examined. Since then, to examine the applicability of the two filter products in indoor spaces, time-series changes were identified in an indoor space of about 10 pyeong (about 3.3 m^2) for PM_{10} and $PM_{2.5}$ from February to March, 2021, and the adsorption performance was evaluated.

Research materials and experimental equipment

The measuring equipment used in this study was the 11-s aerosol spectrometer (Grimm Aerosol Technik, Berlin, Germany), which is a portable real-time fine dust meter. This equipment uses a light scattering method to measure the PM concentration, and can measure 0.24–32 μm particles by dividing them into 31 channels. To evaluate the fine dust removal efficiency of the filter, the differential pressure was measured using a differential pressure gauge (Testo 400; Testo Korea Ltd., Bangkok, Thailand), and a velocity gauge (Air Velocity Transducer 8455; TSI, Shoreview, Minnesota 55126, USA) was used to measure the filtration flow rate. A wind tunnel (Anytech Co., Suwon, Korea) capable of reproducing wind speeds of 0–30 m/s was used to measure the fine particle concentration and analyze the propagation behavior of fine particles according to wind speed. A dust generator was used to spray A1 ultrafine dust (ISO 12103-1), with particle diameters of 0–10 μm. A1 ultrafine dust is composed of aluminum, iron, sodium, calcium, magnesium, titanium, and potassium, with a maximum silicon content of 69–77%. A jig was made for the test, the outside and inside were white acrylic, and the material of the panel inserted into the jig was polycarbonate. The external dimensions were 687 (W) x 698 (D) x 600 (L) mm, the internal dimensions were 491(W) x 491 (D) x 600 (L) mm, and the panel dimensions were 500 (W) x 2 (D) x 600 (L) mm (Figure 1).

Figure 1: The test equipment used to minimize pressure loss for the filter efficiency measurements

The ACF fibers used in this study were imported into the country, whereas the Cerebasel and Cerecore functional filter products were manufactured in Korea. Cerebasel is a product that is laminated by the processing of activated carbon and carbon material layers, and has the feature of being able to be printed onto the surface of a fabric (Figure 2; Tables 1 and 2).

Division	Antibacterial deodorizing water repellent fabric	Nano fiber	Activated carbon non-woven	Antibacterial and deodorizing fabric
Material information	PET (75/72 DTY)	PVDF	Polyester and Carbon	PET (75/36 SDY)
Main functions and features	Antibacterial, deodorizing – zeolite	Dust filtration	Dust filtration and deodorization Specific surface area: 500~600 ㎡/g	Antibacterial, deodorizing – zeolite
Weight	150 gsm	2 gsm	280 gsm	115 gsm
Thickness	0.61 mm	-	3.00 mm	0.48 mm

Table 1: Composition and features of Cerebasel

Division	Antibacterial deodorizing water repellent fabric	Nano fiber	Activated carbon non-woven	Antibacterial and deodorizing fabric
Material information	PET (Mono 20D)	PVDF	Polyester and Carbon	PET (75/72 DTY)
Main functions and features	Antibacterial, deodorizing – zeolite	Dust filtration	Dust filtration and deodorization Specific surface area: 500~600 ㎡/g	Antibacterial, deodorizing – zeolite
Weight	40 gsm	2 gsm	280 gsm	115 gsm
Thickness	0.21 mm	-	3.00 mm	0.61 mm

Table 2: Composition and features of Cerecore

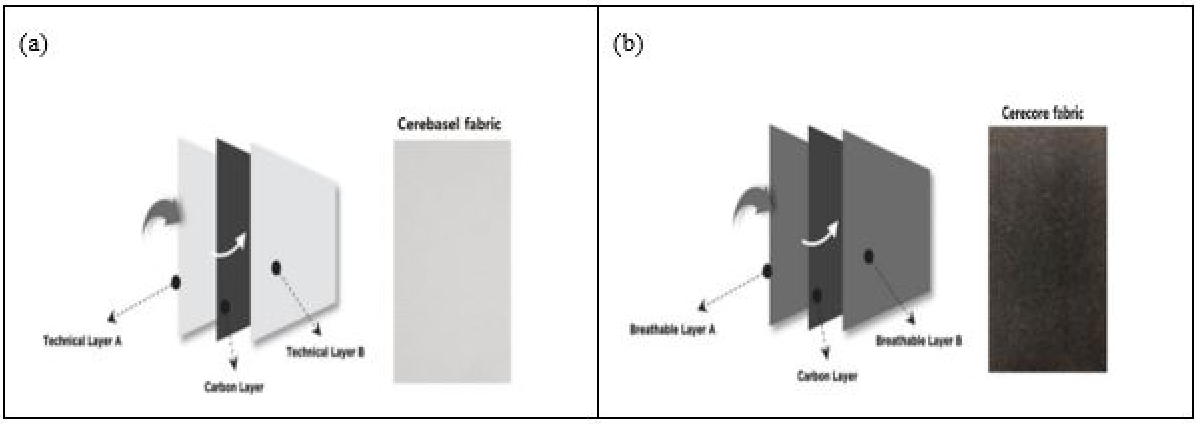

Figure 2: Functional activated carbon non-woven fabric filters **(a)** Cerebasel; **(b)** Cerecore

Experimental methods

In this experiment, a functional activated carbon non-woven fabric filter was passed through a wind tunnel device (700 (W) x 700 (D) x 7,135 (L) mm) and the inflow of fine dust was measured before and after filtration. A1 ultrafine dust was sprayed at a constant concentration, and the PM concentration was simultaneously measured at 6 s intervals using an aerosol spectrometer for 15 min before and after the filter passed through the tunnel. This was repeated three times for each variable to assess the reproducibility of the results. The experimental variables in this study were the PM concentration (PM_{10}, $PM_{2.5}$), filter depth (200, 400, and 600 mm), and wind speed (0.1–5 m/s) (Table 3). Wind speed was the variable. The tunnels in the subway are semi-enclosed spaces, and high-speed trains generate wind as they operate [1,16]. Considering the applicability of the results to roadside locations as well as tunnels, the wind speed was set to 0.1–5 m/s, which represented the average wind speed in each city in Korea. Because the functional activated carbon non-woven fabric filter is a non-powered filter, the energy efficiency was higher when the differential pressure of the filter is low, and therefore the differential pressure for each wind speed was investigated. In this experiment, the optimum conditions for the highest removal efficiency and low differential pressure were determined for each variable. A test jig was constructed and a functional activated carbon non-woven fabric filter was attached to both sides of a panel. The panel was vertically erected in a form that minimized pressure loss during air flow so that fine dust can be attached to both sides (Figure 3). In addition, the experimental results of two domestically manufactured functional activated carbon non-woven fabric filters and the existing ACF filter were analyzed and compared.

A time-series of the fine dust reduction efficiency in the indoor space was examined for the functional activated carbon non-woven fabric filter, and its applicability for a subway environment was reviewed. Based on the existing indoor air quality standards, measurements were made at a height of 1.2–1.5 m from the floor at the center point of the indoor space, and measurements were made at a location at least 1 m from the wall. In addition, to examine the reduction efficiency by applying a fence-type filter to the side of the road, which has been used overseas, the filter was installed in front of the back gate of Yakdae Elementary School in Bucheon City. This enabled the efficiency of fine dust reduction to be assessed, and finally the potential for its application to underground spaces was evaluated.

Particulate matter		**A1 ultrafine test dust (ISO 12103-1)**
Reactor	Duct	Air flow generator (Fine PM propagation path analysis product)
	Size	700 mm X 700 mm X 7,135 mm
Test specimen	Material	(External/Internal) White acrylic (Panel) Polycarbonate
	Size	(External) 698 mm X 698 mm X 600 mm (Internal) 491 mm X 491 mm X 600 mm (Panel) 600 mm X 500 mm X 2 mm
Activated carbon filter	Thickness	3 mm
	Depth	200 mm, 400 mm, 600 mm
	Interval	10 mm
Wind speed		0.1 m/s, 0.5 m/s, 1.0 m/s, 2.0 m/s, 3.0 m/s, 5.0 m/s

Table 3: Summary of the filter performance experiment

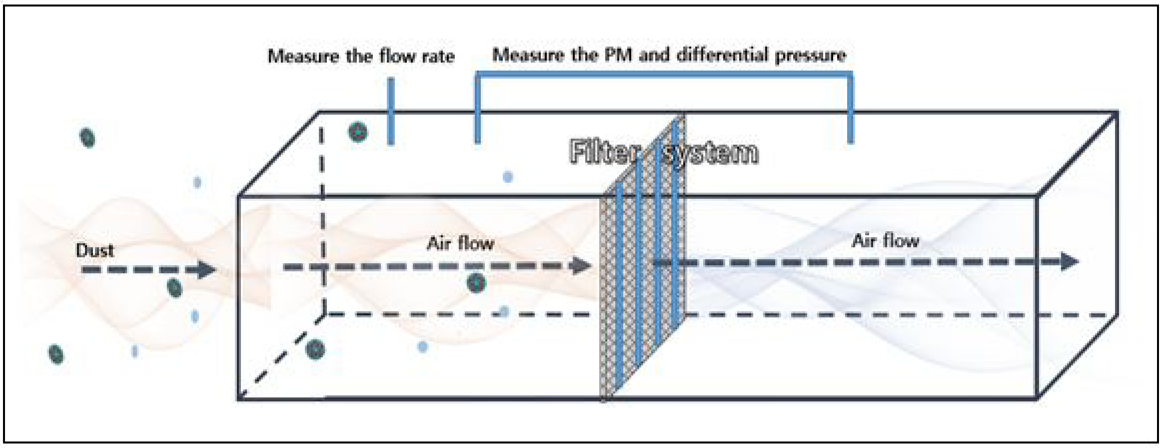

Figure 3: The filter system used to evaluate fine PM filtration performance in this study

Results and Discussion

Particulate matter removal efficiency

The PM concentration (PM_{10}, $PM_{2.5}$), filter depth (200 mm, 400 mm, 600 mm), and wind speed (0.1–5 m/s) were used as the experimental variables.

The average removal efficiencies at a depth of 200 mm for the Cerebasel filter were 5.7% (PM_{10}) and 0.1% ($PM_{2.5}$), and for the Cerecore filter they were 17.1% (PM_{10}) and 10.3% ($PM_{2.5}$), Because it was found that there is almost no efficiency at 0.1~1m/s. So, it was confirmed that Cerecore had high average removal efficiency at both PM_{10} and $PM_{2.5}$. At a wind speed of 3.0 m/s, the average removal efficiencies for the Cerebasel filter were 21.1% (PM_{10}) and 11.6% ($PM_{2.5}$), and for the Cerecore filter the average removal efficiencies were 23.4% (PM_{10}) and 14.8% ($PM_{2.5}$) at a wind speed of 2.0 m/s. For the Cerebasel filter the removal efficiencies of PM_{10} and $PM_{2.5}$ at wind speeds of 2.0–5.0 m/s were above average, and for the Cerecore filter the removal efficiencies of PM_{10} and $PM_{2.5}$ at wind speeds of 1.0–3.0 m/s were also higher than average. For the Cerebasel filter the average removal efficiencies were highest at 3.0 m/s, while the Cerecore filter had the highest removal efficiency at 2.0 m/s. Over the wind speed range of 2.0–3.0 m/s, the removal efficiency for both filters decreased as the wind speed gradually increased (Table 4).

The average removal efficiencies at a depth of 400 mm for the Cerebasel filter were 14.1% (PM_{10}) and 7.2% ($PM_{2.5}$), and for the Cerecore filter were 23.0% (PM_{10}) and 13.6% ($PM_{2.5}$), Because it was found that there is almost no efficiency at 0.1~1m/s. So, it was confirmed that Cerecore had high average removal efficiency at both PM_{10} and $PM_{2.5}$. The average removal efficiencies for the Cerebasel filter were 23.4% (PM_{10}) at a wind speed of 3.0 m/s and 13.3% ($PM_{2.5}$) at a wind speed of 5.0 m/s, while for the Cerecore filter the average removal efficiencies were 36.3% (PM_{10}) and 24.7% ($PM_{2.5}$) at a wind speed of 5.0 m/s. For the Cerebasel filter at wind speeds of 2.0–5.0 m/s, the removal efficiency was above average for both PM_{10} and $PM_{2.5}$. For the Cerecore filter the PM_{10} removal efficiency was above average at wind speeds of 1.0, 3.0, and 5.0 m/s, and the average $PM_{2.5}$ removal efficiency was higher at wind speeds of 3.0–5.0 m/s. For the Cerebasel filter, the highest PM_{10} removal efficiency was observed at 3.0 m/s, while the highest $PM_{2.5}$ removal efficiency was observed at 5.0 m/s. The Cerecore filter had the highest removal efficiency for both PM_{10} and $PM_{2.5}$ at 5.0 m/s. When the depth of the functional activated carbon non-woven fabric filter was doubled from 200 to 400 mm, the efficiency of the Cerebasel filter increased by about 2.5 times for PM_{10}, and the efficiency of the Cerecore filter increased by about 1.3 times for both PM_{10} and $PM_{2.5}$. It was confirmed that the removal efficiency of both PM_{10} and $PM_{2.5}$ increased as the specific surface area of the filter increased (Table 5).

Wind speed (m/s)	Cerebasel						Cerecore					
	PM_{10}			$PM_{2.5}$			PM_{10}			$PM_{2.5}$		
	Before filtration (μg/m³)	After filtration (μg/m³)	Removal efficiency (%)	Before filtration (μg/m³)	After filtration (μg/m³)	Removal efficiency (%)	Before filtration (μg/m³)	After filtration (μg/m³)	Removal efficiency (%)	Before filtration (μg/m³)	After filtration (μg/m³)	Removal efficiency (%)
0.1	137.9 ± 23.9	160.9 ± 24.9	-	72.4 ± 10.5	82.3 ± 10.5	-	131.9 ± 18.4	117.8 ± 15.4	10.7	71.7 ± 8.3	66.9 ± 7.5	6.8
0.5	144.5 ± 17.0	149.8 ± 16.6	-	72.7 ± 7.9	77.5 ± 7.7	-	143.9 ± 36.7	119.1 ± 36.7	17.3	74.7 ± 15.6	66.4 ± 16.4	11.1
1	131.8 ± 14.9	131.6 ± 14.0	-	69.8 ± 6.9	72.6 ± 6.7	-	130.8 ± 13.3	106.2 ± 11.3	18.8	72.8 ± 5.7	65.0 ± 5.5	10.7
2	123.8 ± 12.5	102.2 ± 9.4	17.4	65.4 ± 5.4	60.4 ± 4.4	7.5	138.7 ± 16.7	106.2 ± 12.6	23.4	82.0 ± 9.3	70.7 ± 7.6	14.8
3	146.2 ± 19.3	115.2 ± 15.4	21.1	77.7 ± 8.7	68.5 ± 7.6	11.6	133.7 ± 9.4	109.1 ± 8.7	18.4	87.7 ± 4.8	78.5 ± 4.6	10.8
5	125.6 ± 14.7	102.4 ±13.8	17.8	68.3 ± 6.8	61.5 ± 6.3	9.9	126.7 ± 13.0	109.3 ± 10.8	13.7	84.9 ± 6.5	78.5 ± 5.7	7.5

Table 4: Average removal efficiency of fine PM for the Cerebasel amd Cerecore filter according to wind velocity (ACF depth 200 mm)

Wind speed (m/s)	Cerebasel						Cerecore					
	PM_{10}			$PM_{2.5}$			PM_{10}			$PM_{2.5}$		
	Before filtration (μg/m³)	After filtration (μg/m³)	Removal efficiency (%)	Before filtration (μg/m³)	After filtration (μg/m³)	Removal efficiency (%)	Before filtration (μg/m³)	After filtration (μg/m³)	Removal efficiency (%)	Before filtration (μg/m³)	After filtration (μg/m³)	Removal efficiency (%)
0.1	133.3 ± 25.1	128.1 ± 23.1	3.5	67.0 ± 11.0	66.4 ± 9.5	0	134.2 ± 22.2	117.7 ± 17.5	12.2	65.7 ± 9.1	61.4 ± 7.8	6.9
0.5	133.6 ± 26.0	124.6 ± 24.8	7.0	65.7 ± 9.5	64.1 ± 8.1	2.8	134.7 ± 19.7	116.1 ± 15.9	13.8	65.4 ± 7.8	60.7 ± 6.3	7.4
1	128.7 ± 14.5	117.4 ± 13.6	8.9	67.0 ± 6.8	65.3 ± 6.2	3.0	134.8 ± 14.4	103.0 ± 12.0	23.4	68.5 ± 7.5	59.5 ± 6.9	13.2
2	137.6 ± 15.8	110.4 ± 11.5	19.3	74.8 ± 6.9	66.4 ± 5.3	10.9	142.8 ± 20.2	111.4 ± 16.8	21.8	82.9 ± 11.1	74.5 ± 10.6	10.4
3	122.7 ± 18.9	94.0 ± 13.6	23.4	69.4 ± 6.8	60.5 ± 5.0	13.1	134.5 ± 18.1	93.8 ± 11.6	30.3	79.9 ± 9.3	65.0 ± 6.8	19.4
5	130.1 ± 16.0	100.8 ± 11.8	22.4	70.6 ± 6.0	62.1 ± 4.7	13.3	122.7 ± 15.2	78.1 ± 19.2	36.3	69.1 ± 6.5	525.0 ± 5.9	24.7

Table 5: Average removal efficiency of fine PM for the Cerebasel amd Cerecore filter according to wind velocity (ACF depth 400 mm)

The average removal efficiencies at a depth of 600 mm for the Cerebasel filter were 20.7% (PM_{10}) and 12.0% ($PM_{2.5}$) and for the Cerecore filter were 37.6% (PM_{10}) and 27.3% ($PM_{2.5}$). It was confirmed that Cerecore had high average removal efficiency at both PM_{10} and $PM_{2.5}$. At a wind speed of 5.0 m/s, the Cerebasel filter had removal efficiencies of 37.7% (PM_{10}) and 24.1% ($PM_{2.5}$), while the Cerecore filter had removal efficiencies of 53.5% (PM10) and 40.3% ($PM_{2.5}$) at a wind speed of 3.0 m/s. For the Cerebasel filter, there were above-average removal efficiencies for PM_{10} at wind speeds of 2.0–5.0 m/s, and $PM_{2.5}$ at wind speeds of 3.0–5.0 m/s. The Cerecore filter had higher than average removal efficiencies for both PM_{10} and $PM_{2.5}$ at wind speeds of 2.0–5.0 m/s. In addition, when the depth of the functional activated carbon non-woven fabric filter was increased from 400 to 600 mm, the removal efficiencies of the Cerebasel and Cerecore filters increased by more than 1.5 times for PM_{10} and $PM_{2.5}$. For the Cerecore filter, the removal efficiency of PM_{10} was more than 50% at wind speeds of 3.0–5.0 m/s (Table 6).

Wind speed (m/s)	Cerebasel						Cerecore					
	PM_{10}			$PM_{2.5}$			PM_{10}			$PM_{2.5}$		
	Before filtration (μg/m³)	After filtration (μg/m³)	Removal efficiency (%)	Before filtration (μg/m³)	After filtration (μg/m³)	Removal efficiency (%)	Before filtration (μg/m³)	After filtration (μg/m³)	Removal efficiency (%)	Before filtration (μg/m³)	After filtration (μg/m³)	Removal efficiency (%)
0.1	133.3 ± 18.6	125.6 ± 14.7	6.0	88.6 ± 8.8	86.2 ± 6.7	3.4	130.6 ± 25.7	107.2 ± 16.6	17.9	51.8 ± 11.7	44.5 ± 7.3	14.0
0.5	143.2 ± 14.5	126.0 ± 12.2	12.0	94.6 ± 7.4	88.0 ± 6.0	7.1	137.5 ± 19.1	103.4 ± 13.7	24.6	56.9 ± 8.6	46.4 ± 6.4	18.5
1	130.1 ± 11.5	108.7 ± 9.7	16.4	89.1 ± 5.8	81.3 ± 5.0	8.9	141.2 ± 18.7	96.2 ± 13.6	32.4	60.4 ± 8.1	47.4 ± 6.6	22.5
2	140.1 ± 13.6	108.1 ± 8.5	23.2	97.7 ± 6.5	86.7 ± 4.4	11.8	137.4 ± 22.0	76.0 ± 12.4	44.7	57.8 ± 8.4	40.0 ± 5.5	31.6
3	141.2 ± 11.7	100.6 ± 8.7	28.7	99.2 ± 5.3	83.4 ± 4.1	16.5	134.7 ± 24.3	62.5 ± 11.8	53.5	55.5 ± 8.3	33.3 ± 5.0	40.3
5	118.8 ± 11.0	74.0 ± 6.3	37.7	82.8 ± 4.1	62.8 ± 2.7	24.1	130.6 ± 22.7	62.6 ± 10.2	52.2	64.1 ± 10.3	40.8 ± 6.0	36.6

Table 6: Average removal efficiency of fine PM for the Cerebasel amd Cerecore filter according to wind velocity (ACF depth 600 mm)

It was confirmed that the removal efficiency of the two functional activated carbon non-woven fabric filters was not high at 0.1–0.5 m/s, but the average PM removal efficiency was high at 2.0–5.0 m/s. This shows a tendency similar to the experimental results obtained for the existing ACF filter, but unlike the existing ACF filter the Cerebasel and Cerecore filters had a high removal efficiency even at a wind speed of 5.0 m/s. It was also apparent that the adsorption performance of the filters was strong.

Wind speed has a major influence on PM generation. When the wind speed was low, the PM did not reach the filter, making it difficult to adsorb. When the wind speed was high, the air flow became unstable as it rapidly passed through the wind tunnel, making it difficult to adsorb PM on the filter.

In addition to wind speed as an experimental variable, the cross-sectional area of the filter was also a very important factor. As a result of examining various filter cross-sectional areas and wind speeds, it was confirmed that the differential pressure was low at wind speeds of 2.0–5.0 m/s, and the smaller the cross-sectional area, the lower the differential pressure (Table 7). As the wind speed increased, the flow rate increased, and when the friction loss increased according to the cross-sectional area, the differential pressure increased, which led to a decrease in the efficiency of PM collection by the filter. When the total depth was 600 mm and the wind speed was 3.0 m/s, the Cerecore filter had the highest removal efficiencies of 53.5% (PM_{10}) and 40.3% ($PM_{2.5}$). In contrast, when the Cerebasel filter had a total depth of 600 mm and the wind speed was 3.0 m/s, the removal efficiencies were 37.7% (PM_{10}) and 24.1% ($PM_{2.5}$), indicating that the adsorption performance was slightly lower than that of the existing ACF filter.

Sample condition	Pressure loss (Pa)					
	200 mm		400 mm		60 mm	
	Cerebasel	Cerecore	Cerebasel	Cerecore	Cerebasel	Cerecore
0.1 m/s	3.9	1.0	5.2	3.1	1.1	4.7
0.5 m/s	3.1	7.2	2.5	6.9	12.8	8.4
1 m/s	15.2	24.6	18.9	35.0	40.1	50.0
2 m/s	79.5	98.7	82.0	117.1	147.7	172.4
3 m/s	149.0	174.5	156.0	215.4	266.0	327.2
5 m/s	177.2	223.6	317.5	400.3	510.7	513.2

Table 7: Differential pressure characteristics of the ACF at different wind speeds

Optimal conditions and field application review

In this study, the depth, wind speed, differential pressure, and PM concentration on the filter were comprehensively reviewed as experimental variables, and the optimal conditions for the application of non-powered functional activated carbon non-woven fabric filters in underground spaces were determined. The Cerecore filter was found to be a domestically manufactured filter with the potential to replace ACFs, which are imported into Korea. The optimal efficiency was obtained when the filter depth was 600 mm and the wind speed was 3.0 m/s (Figure 4).

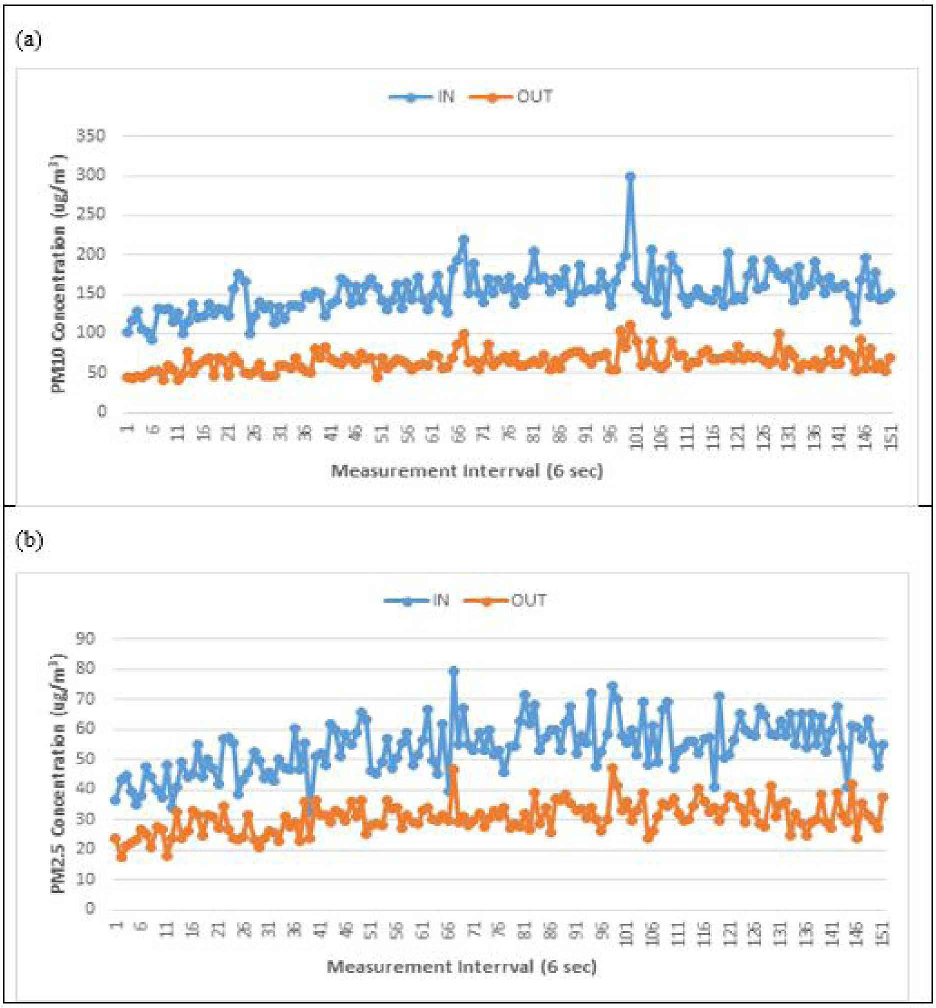

Figure 4: Variation in fine PM removal efficiency under optimal conditions for a Cerecore filter with a depth of 600 mm at a flow rate of 3.0 m/s; **(a)** PM_{10}; **(b)** $PM_{2.5}$

To examine the applicability of the Cerebasel and Cerecore filters used in this study for applications in underground spaces, a time-series of the variation in PM collection was determined and the adsorption performance was confirmed. As a result, the removal efficiency was determined to be 63.10% for PM_{10} and 63.21% for $PM_{2.5}$ in the Cerebasel filter in an indoor space of about 10 pyeong (about 3.3 m^2). The removal efficiency of the Cerecore filter was 65.7% for PM_{10} and 66.5% for $PM_{2.5}$. Similar to the test results obtained when examining the filter efficiency according to panel manufacturing, it was confirmed that the removal efficiency of the Cerecore filter was slightly higher.

In addition, to examine the fine dust reduction efficiency of a non-motorized functional activated carbon non-woven fabric filter in a roadside location, a Cerebasel filter was printed on the surface of the fabric, on the back door of Yakdae Elementary School in Bucheon. This produced a practical and aesthetic application of the filter and the fine dust reduction performance of the filter in the fence was evaluated. The PM removal efficiency of the filter installed in the panel-type fence was 19.5% for PM_{10} and 24.9% for $PM_{2.5}$, and the wind speed of the school commuting route was 0.3–0.4 m/s, which was very low (Figure 5). The flow rate is a major factor in the examination of filter adsorption capacity, and although the flow rate was very low on the roadside, it was confirmed that the filter could remove fine dust from the air and had a strong adsorption capacity. It was concluded that the Cerebasel filter could contribute to the improvement of indoor air quality and was suitable for applications in underground spaces.

Figure 5: Measurement of the fine PM reduction efficiency of a Cerebasel filter in Bucheon City

Conclusions and Discussion

Pollutants that affect indoor air quality include volatile organic compounds (VOCs), fine dust, and bio-aerosols. In this study, the adsorption method and capacity of selected filters were investigated. The pressure loss during the removal of fine dust was minimized using a non-powered functional activated carbon non-woven fabric filter as an adsorbent. In particular, the removal efficiency and optimal conditions of the non-powered functional activated carbon non-woven fabric filter were determined and compared with existing ACF filters, and the removal efficiency in indoor and underground spaces, such as subway tunnels and stations, was evaluated.

A commercial ACF is a non-woven fabric with a large specific surface area, high adsorption rate and capacity, light weight, and excellent flexibility and malleability. However, because Korea is entirely dependent on imports of ACFs, we designed a panel-type prototype with a minimal pressure loss using domestically manufactured laminated fiber filters (Cerebasel and Cerecore) as a replacement. It was confirmed that the Cerecore filter had a slightly higher reduction efficiency than the Cerebasel filter, and the optimal efficiency was obtained with a filter depth of 600 mm and air flow rate of 3 m/s. In the existing ACF filter system of the previous study, the optimal conditions were when the ACF depth was 400 mm and the airflow velocity was 3.0 m/s. However, the laminated fiber filters used in this study required a larger area of 600mm, but it was confirmed that the optimum condition was when the airflow speed was the same 3.0m/s. In addition, to confirm the ability of the laminated fiber filters to reduce fine dust levels in underground spaces, such as subway tunnels and stations, and improve their aesthetics, a fence-type filter was manufactured and used on the roadside of a school in Bucheon City. Its dust removal efficiency was determined.

It was concluded that wind speed is a very important variable, but the filter could be applied in a subway tunnel space, which would be affected by the airflows generated by passing trains. In addition, the non-powered functional activated carbon non-woven fabric filter used in this study can be washed and reused, and because it is economically more cost-effective, it will be applicable not only to subway locations but also to various other spaces where air quality improvements are required. In this study, the efficiency in indoor and outdoor spaces was examined, and although the efficiency was relatively low, the non-powered filter still had potential practical applications. In the future, it will be necessary to derive the optimal conditions for different environmental locations by installing the currently developed panel-type filter system on the roadside and comparing the reduction efficiency of non-powered functional activated carbon non-woven fabric filters and existing ACF filters.

Author Contributions

Park D planned the study and contributed the main ideas; Kim M-K was principally responsible for the writing of the manuscript; Seo C S revised the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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