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Influence of Aging Time on Filtration Performance of P84 Filter Media with Seam

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Cite This: *ACS Omega* 2024, 9, 10709–10716

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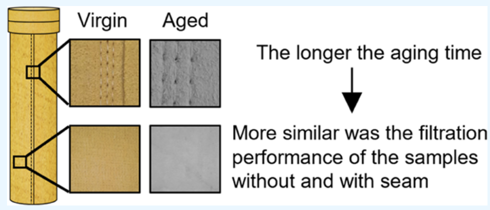
ABSTRACT: Although the area with the seam is approximately 4% of the total area of an industrial filter bag, a more extensive investigation of the influence of this region on surface filtration is necessary since the small seam holes can be a conduit for the passage of fine particles even after a certain time of use of the filter bag. Therefore, this work aimed to assess the influence of aging time on the filtration performance of P84 filter bags (samples without and with seam) used in an industrial bag filter, regarding tensile mechanical properties, air permeability, fractional separation efficiency, and filtration cycles. The particulate matter applied (sinter dust) to evaluate the efficiency and to perform the cycles was collected in the hoppers of an industrial bag filter installed in the primary dedusting system of a sinter plant in the steel industry. The results showed that the filter bag aged for 10 months presented a fractional separation efficiency of almost 100%, even for the samples with a seam, suggesting that the seam holes were sealed by the powder in the industrial installation. As for the tensile mechanical properties, the tests showed that the aging of the filter bag caused a reduction in the tensile strength of the filter medium. With respect to air permeability and filtration cycles, the longer the aging time of the filter bag, the more similar was the filtration performance of the samples without and with seam.



1. INTRODUCTION

It is estimated that 99% of the entire world population is exposed to air pollution levels that exceed the quality limits recommended by the World Health Organization (WHO). Human exposure to polluted air causes about 7 million deaths annually worldwide, which result from the penetration of fine particles through the airways and bloodstream, causing heart disease, stroke, chronic obstructive pulmonary disease, cancer, and pneumonia.[1]

There is a diversity of equipment for air pollution control in industries, such as cyclones, gas scrubbers, electrostatic precipitators, bag filters, and hybrid filters. The choice of the appropriate equipment for each specific process should consider the type of particulate matter, including particle size distribution, abrasiveness, hygroscopicity, and concentration, as well as consider the characteristics of the process gas stream, such as chemical composition, corrosiveness, temperature, humidity, and flow rate.

Bag filters with pulse-jet cleaning systems are often used in dry processes. This is because the polluted air passes through a large bag filter area and the separated dust forms a cake on the filter medium surface; therefore, it generally works with high separation efficiency. If this dust layer is thick enough, the particles can be separated almost completely, resulting in a very low concentration on the clean gas side. As the cake thickness increases, so does the pressure drop, which is why the cake is periodically removed from the filter bag surface, reducing the pressure drop and enabling long-term economical operation. Regeneration by pulse-jet cleaning is done at regular time intervals (Δt control) or at specified limits of maximum differential pressure (Δp control). Removing the cake leads to an increase in the particle concentration on the clean gas side immediately after regeneration because particles can penetrate the filter medium for a short period of time. As the cake is newly formed, the particle concentration decreases again. For bag filter application, the filter medium is usually manufactured in a cylindrical form, so that the filter elements can be installed efficiently. A typical way of making cylindrical filter bags is by sewing the filter material.

There are studies in the literature related to the evaluation of small coupons in filter test rigs (Bach; Schmidt, 2007;[2] Mouret et al., 2009;[3] Mukhopadhyay; Mahawar, 2020;[4] Li et al., 2022[5]), in pilot plant-scale baghouses (Mukhopadhyay; Choudhary, 2013;[6] Kurtz; Meyer; Kasper, 2017;[7] Bächler et al., 2020;[8] Bächler et al., 2022[9]), and investigation in industrial plants (Tomanovich; Knotts, 2013[10]) that have researched the particulate emissions caused by small holes, made on purpose

Received: November 25, 2023
Revised: February 3, 2024
Accepted: February 6, 2024
Published: February 20, 2024

https://doi.org/10.1021/acsomega.3c09037
ACS Omega 2024, 9, 10709–10716

in the fabric, with defined diameters (pinholes), as well as the seam holes. All of these authors have concluded that the holes can greatly contribute to the overall dust emission, as presented in the work of Lacerda et al., 2022.[11]

More recently, Bächler, Meyer, and Dittler 2022[12] applied a low-cost PM sensor network to a small-scale bag filter for online spatial monitoring of several types of particle emission hotspots from each filter bag. They investigated the spatial identification of a filter bag with open seams (the seams allowed greater particle penetration during initial filter cycles) and demonstrated how the increasing number of small leaks of a few millimeters in diameter in a single filter bag affected the measurement and detection capabilities of low-cost PM sensors. Tests on the small-scale bag filter showed the potential to reliably identify leaks as well as the potential to estimate leak sizes by correctly interpreting the sensor data.

Most of these studies have performed experiments using factory-new filter bags. Therefore, the present work proposed to analyze the seam region of filter media, which were previously aged at different times in an industrial bag filter, in terms of tensile mechanical properties, air permeability, fractional separation efficiency, and filtration cycles.

2. MATERIALS AND METHODS

This section presents the material, the methodologies, and the description of the test rigs used to perform the tests with virgin, 10-month-aged, and 3-year-aged samples of P84 filter bags, as well as the characterization of the filter media and the particulate matter.

2.1. General Description of the Filter Bags: Virgin, 10 Months, and 3 Years of Use. The samples were taken from three filter bags, one virgin and two with different times of use in a bag filter of a sinter plant of the steel industry: one with 10 months and another with 3 years of use. The gas inlet temperature to the sinter plant bag filter in 2023 was 173 °C on average, with a maximum temperature of 200 °C. The operating environment is acidic due to the presence of sulfur, and humidity is around 10%. All filter bags are composed of P84 needlefelt with fine multilobal P84 fibers, with singed finishing on the external faces, and they also had longitudinal triple seams.

The technical specifications of the virgin P84 filter bag, supplied by the manufacturer, are shown in Table 1.

Table 1. Technical Specifications of the Virgin P84 Filter Bag Provided by the Manufacturer

grammage[a]	710 g·m^{-2}
thickness[b]	1.0 mm
density	0.44 g·cm^{-3}
air permeability at 20 mmH_2O[c]	80 L·dm^{-2}·min^{-1}

[a]DIN EN 29073—part 1. [b]DIN EN ISO 9073—part 2. [c]DIN EN ISO 9237.

The filter bags, virgin and used, had the following dimensions: 0.16 m in diameter and 8.00 m in length, providing a surface area of 4.06 m^2 (Figure 1). In an entire filter bag, the area of the seam where there are overlapping fabrics, highlighted in yellow in Figure 1, is equal to 0.15 m^2, which represents approximately 4% of the total area.

The samples taken for the permeability tests were 0.0715 m in diameter, which corresponded to a total area of approximately 0.0040 m^2, with the seam area equal to 0.0014 m^2, which represents 35% of the total area. The samples used in the fractional separation efficiency tests had a diameter of 0.0473 m, with a total filtration area of approximately 0.0018 m^2 and a seam area of 0.0009 m^2, representing 50% of the total area. In the filtration tests in the VDI 3926 test rig, the diameter of the samples was 0.160 m, with a total filtration area of 0.0201 m^2 and the seam area equal to 0.0030 m^2, corresponding to 15% of the total area. The samples taken from the filter bags, on the areas without and with seams, are shown in Figure 2.

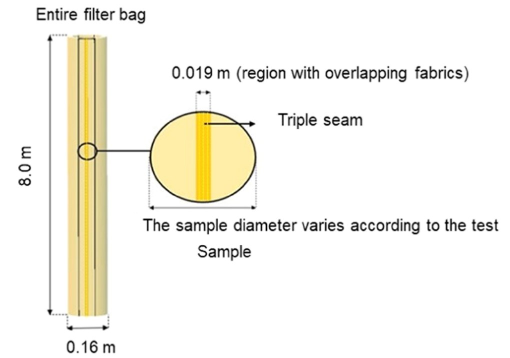


Figure 1. Dimensions of the entire filter bag and illustration of a sample taken in the region with seam.

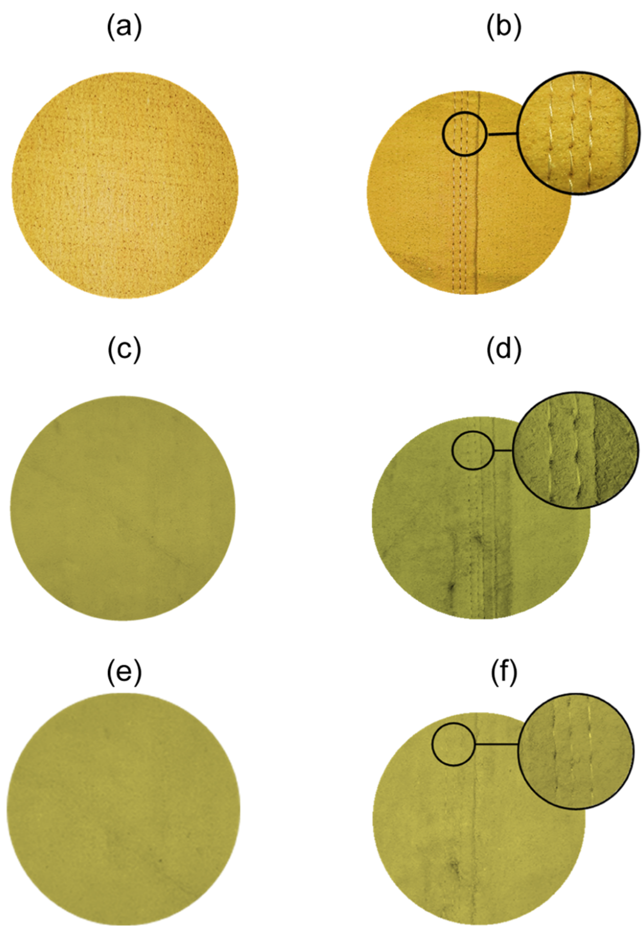


Figure 2. Photograph of the samples: without (a) and with (b) seam taken from the virgin filter bag; without (c) and with (d) seam taken from the filter bag aged for 10 months; without (e) and with (f) seam taken from the filter bag aged for 3 years.

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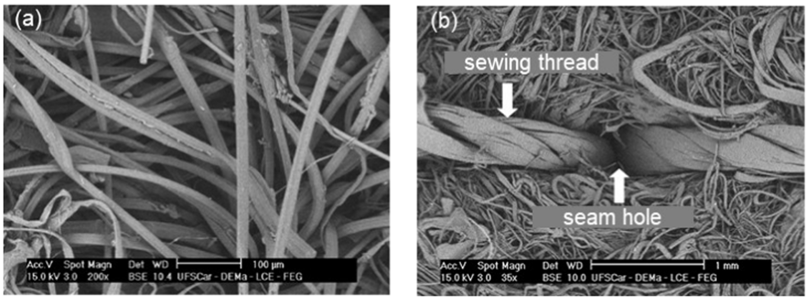

Figure 3. SEM of the outer surface of the virgin P84 sample, the region without seam (a), and the region with seam (b).

2.1.1. Mean Fiber Diameter and Sewing Thread. The mean fiber diameter was determined according to the methodology proposed by Bortolassi, Guerra, and Aguiar.[13] Images of the filter media were obtained in the scanning electron microscope, Philips brand, and model XL-30 FEG (field emission gun). Samples of 1 cm × 1 cm of the virgin filter medium, with and without seam, were coated with a thin layer of gold. Six images of each sample were obtained, in different positions, with 200 times magnification and back-scatter detector (BSE) (Figure 3a).

For the determination of the mean diameter of the sewing thread, six images of the sample with seam were used (3 − *b*), with 35× magnification, and the sewing thread diameter was measured by Image Pro Plus 7.0. The arithmetic mean of the six measured values was estimated.

The mean diameters of the fibers and of the sewing thread are shown in Table 2.

Table 2. Mean Fiber and Sewing Thread Diameters of the P84 Filter Bag

	mean diameter (μm)
fiber	17.7 ± 9.4
sewing thread	400 ± 3

2.2. General Description of the Particulate Matter: Sinter Dust. In the sinter plant of the steel industry from which the used filter bags were collected, the combustion gases coming out of the sinter strand are filtered by an electrostatic precipitator and in series by a bag filter, in which there is a continuous injection of hydrated lime to create the precoat in the bags during the operation. The dust used in the experiments was taken from the bag filter hoppers. Therefore, this powder is not only the material from the sintering process but also the material from the lime injection. A photograph of this powder and a SEM image are shown in Figure 4.

The powder was sieved through a 0.500 mm (32 mesh) particle sieve for homogenization and dried in an oven at 68 °C for 24 h to remove moisture. When taken out of the oven, the powder was immediately sent to the site of analysis and/or experiment to avoid absorption of moisture from the environment since the material is hygroscopic. When it was necessary to cool the powder to room temperature, a desiccator was used.

2.2.1. Particle Size Distribution in Volume. The particle size distribution in the volume of the sinter dust was determined in the Malvern Mastersizer MicroPlus.

Figure 5 shows the frequency curve (% volume) and the cumulative concentration curve (% volume) of the sinter dust as functions of the volumetric diameter. The median volumetric diameter of the powder was 8.71 μm.

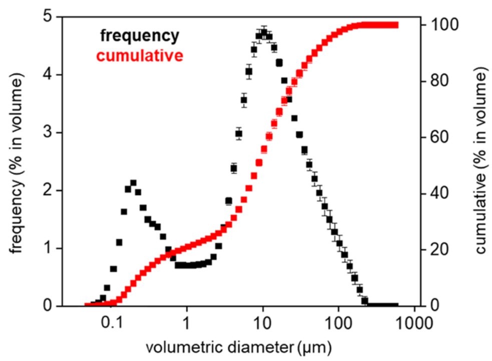

Figure 5. Particle size distribution in the volume of the sinter dust.

2.3. Mechanical Tensile Test. The tensile test was carried out in accordance with ASTM D882:2012[14]—standard test method for tensile properties of thin plastic sheeting—on an Instron model 5969R universal testing machine with a 500 N load cell and a test speed of 12.5 mm/min on five specimens of the virgin filter bag and five specimens of the filter bag used for 3 years.

2.4. Air Permeability Tests. The tests to determine the Darcian permeability coefficient (k_1) were performed for the samples without and with seam of virgin and aged filter bags.

The test rig used is schematically illustrated in Figure 6.

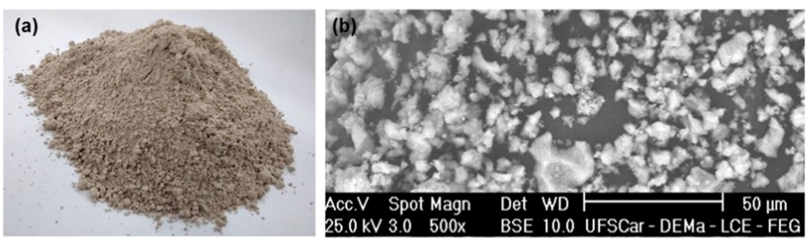

Figure 4. Photograph (a) and SEM image (b) of sinter dust.

https://doi.org/10.1021/acsomega.3c09037
ACS Omega 2024, 9, 10709−10716

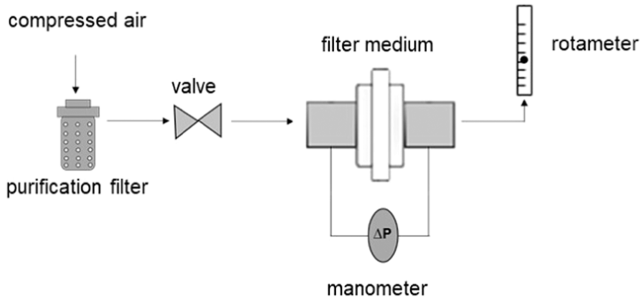

Figure 6. Schematic diagram of the test rig used to determine the Darcian permeability constants (k_1) of the filter media.

The test rig shown in Figure 6 was composed of compressed air, which passed through a purification system in filters to remove moisture and impurities, a valve for flow control, the support for the filter medium, the digital manometer TSI VelociCalc Plus 9555P that measures the differential pressure in the filter medium, and the rotameter Gilmont *N*o. Fourteen CP90533 at the end of the line to measure the volumetric flow rate of air.

Six different flow rates (Q) were adjusted (10, 20, 30, 40, 50, and 60 L·min^{-1}), and the corresponding values of pressure drop in the manometer were obtained. This operation was performed in triplicate for all samples without and with seam, virgin, and used filter bags, with a useful filtration area equal to 0.0040 m^2.

The Forchheimer eq 1 was used to calculate the Darcian permeability coefficient (k_1), disregarding the nonlinear term, since the flow through the filter media could be considered purely viscous for the velocity evaluated

$$\frac{\Delta P}{L} = \frac{v \cdot \mu}{k_1} + \frac{v^2 \cdot \rho}{k_2} \tag{1}$$

where ΔP is the pressure drop in Pascal, L is the thickness of the filter medium in meter, v is the surface velocity in m·s^{-1}, μ is the dynamic air viscosity in Pa·s, and ρ is the air density in kg·m^{-3}.

For gases, the variation of dynamic viscosity with temperature can be approximated by Sutherland's law, eq 2

$$\mu = \mu_0 \cdot \left(\frac{T}{T_0}\right)^{1,5} \cdot \left(\frac{T_0 + S}{T + S}\right) \tag{2}$$

where μ_0 is the reference dynamic viscosity of air at 273.15 K (1.72×10^{-5} Pa·s); T_0 is the reference temperature (273.15 K); S is the Sutherland temperature for air (110.4 K), and T is the temperature of air in Kelvin. The density (ρ) of air can be calculated by the ideal gas law, eq 3

$$\rho = \frac{PM}{RT} \tag{3}$$

where P is the air pressure in Pascal, M is the molar mass of air (0.029 kg·mol^{-1}), R is the universal constant of ideal gases (8.314 J·mol^{-1}·K^{-1}), and T is the air temperature in Kelvin.

2.5. Fractional Separation Efficiency. The fractional separation efficiency was determined for the virgin and aged P84 filter media, with and without seam, using sinter dust. The tests were performed in triplicate, using the sinter dust, with a filtration surface velocity of 2 m·min^{-1}. Figure 7 shows a schematic diagram of the test rig used, comprising an aerodynamic particle sizer (APS), model 3320 from TSI, coupled with an aerosol diluter, model 3302 from TSI, a small-powder disperser, model 3433 from TSI, a filter medium, and sampling probes.

The surface filtration velocity was 2 m·min^{-1}. Isokinetic samplings were collected upstream of the filter medium through sampling probe number 1 and downstream of the filter medium through sampling probe number 2.

The fractional separation efficiency (E) was determined using eq 4, where C_i refers to the particle concentration upstream of the filter medium, collected through sampling probe number 1, and C_f refers to the particle concentration downstream of the filter medium, collected through sampling probe number 2

$$E(\%) = \left[\frac{C_i - C_f}{C_i}\right] \cdot 100 \tag{4}$$

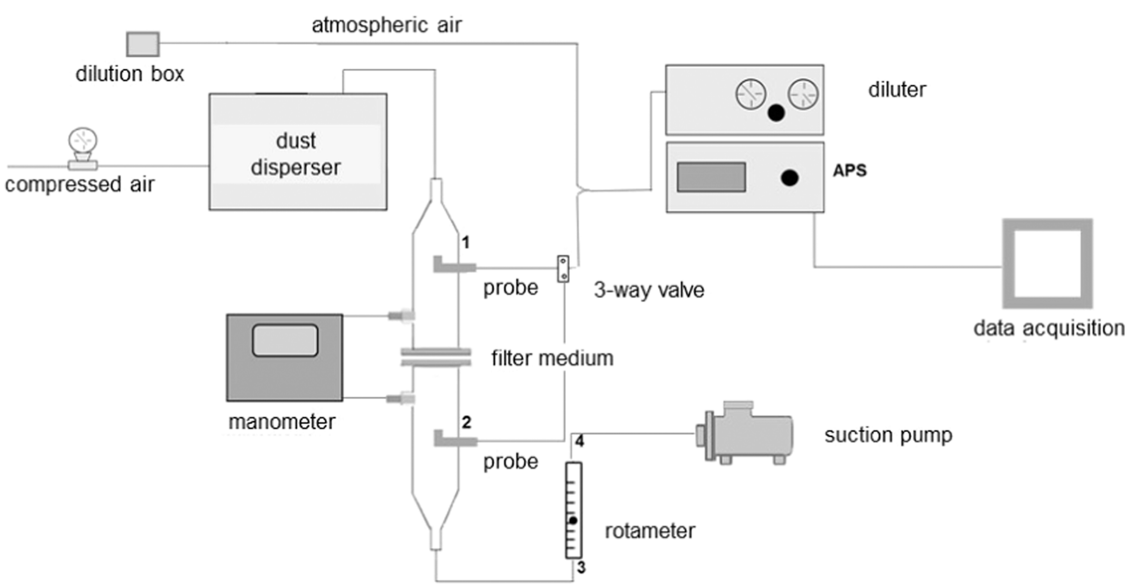

Figure 7. Schematic diagram of the test rig used to determine the fractional separation efficiency.

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ACS Omega 2024, 9, 10709−10716

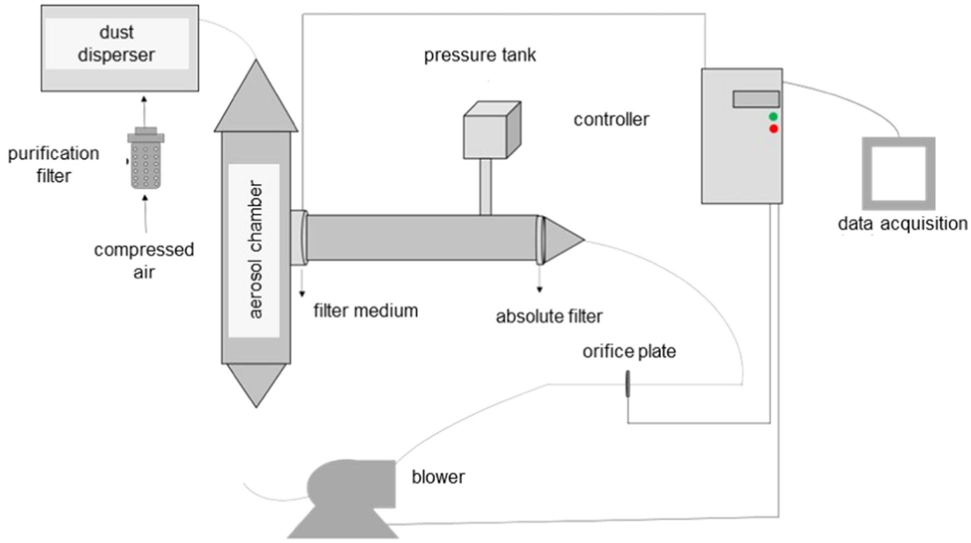

Figure 8. Schematic diagram of the test rig built according to VDI 3926 parameters.

2.6. Filtration Cycles with Pulsed Air Jet Cleaning. The filtration cycles were performed in the test rig, schematically shown in Figure 8. This system was built according to the parameters of the German standard VDI 3926, and the operating conditions used in the experiments also followed the referred standard.

The pressure drop in the filter medium was monitored over time. The pulse-jet cleaning was activated when the pressure drop reached 1000 Pa, the tank pressure was 5 bar, and the valve opening time for cleaning was 60 ms, according to the VDI 3926 standard. Room temperature was about 26 °C, and relative humidity was below 50%.

The filtration cycles were performed with a surface velocity of 2 $m \cdot min^{-1}$, with particulate matter concentration (sinter dust) equal to 5 $g \cdot m^{-3}$. Thirty filtration cycles with pulse-jet cleaning were performed for the virgin samples without and with seam, representing the first stage of the filtration procedure from the VDI 3926 guideline, called the filter medium conditioning. In this stage, the filtration cycles are unstable, and fluctuations of the residual pressure drop and cycle time may occur. For the samples aged for 10 months and 3 years, there was naturally an aging process of the filter bag in the industrial bag filter. Therefore, the 30 cycles performed with these samples correspond to the last stage of the filtration procedure from the VDI 3926 guideline, called measurement, in which the filter medium has already undergone all of the necessary processes to ensure more stable results of pressure drop, cycle time, and separation efficiency.

3. RESULTS AND DISCUSSION

This section presents the influence of the aging time of P84 filter bags, samples without and with seam, on mechanical tensile properties (3.1), air permeability (3.2), fractional separation efficiency (3.3), and filtration cycles (3.4). Before the tests, the filter bags had been in use in industrial installation from zero, namely, virgin filter bag, to 3 years.

3.1. Influence of Aging Time of P84 Filter Bags on Mechanical Tensile Properties. Table 3 shows the tensile mechanical properties of the virgin and 3-year-aged samples without seam.

The values in Table 3 show that aging the filter bag for 3 years has caused the tensile strength to become lower

Table 3. Tensile Mechanical Properties According to ASTM D882

sample	tensile strength (MPa)	deformation at break (%)
virgin filter bag	14.02 ± 0.54	41.21 ± 1.75
3-year-aged filter bag	12.25 ± 0.46	8.89 ± 0.54

compared to the virgin filter bag, i.e., the filter bag used for 3 years withstands a lower maximum tensile strength than the virgin bag. Consequently, the virgin filter bag showed greater deformation until rupture. These results point to the fact that the acidic environment in which the filter bags are exposed, as well as the operating temperature and cleaning cycles have caused wear on the filter medium and made it more prone to breakage.

3.2. Influence of Aging Time of P84 Filter Bags on Air Permeability. The increase of pressure drop through the filter media as a function of the increase of the filtration surface velocity is presented in Figure 9, according to the Forchheimer equation. The tests were performed in triplicate with three different samples taken along the length of each filter bag, in regions without seam and with seam, using compressed air without adding particulate matter, following the procedure described in Section 2.4.

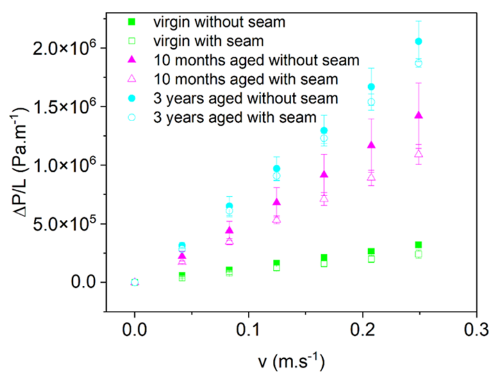

Figure 9. Pressure drop per thickness of P84 filter media as a function of the filtration surface velocity: samples without and with seam with different aging times.

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ACS Omega 2024, 9, 10709−10716

The longer the time of use of the filter bag in industrial installation, the bigger the pressure drop per thickness of the filter media, without and with seams, for all filtration surface velocities evaluated, as can be seen in Figure 9. However, comparing the samples of the same age, the pressure drop of the samples without seam were higher than the pressure drop of the samples with seam, which can be explained by the seam holes in samples with seam, which reduce the resistance to airflow.

The experimental values of the Darcian permeability constants (k_1) of all samples evaluated are shown in Table 4.

Table 4. Darcian Permeability Constants (k_1) of Samples without and with Seam: Virgin, 10-Month-Aged and 3-Year-Aged

	k_1 (m^2)	
	sample without seam	sample with seam
virgin	$(1.45 \pm 0.09) \times 10^{-11}$	$(1.95 \pm 0.27) \times 10^{-11}$
10-month-aged	$(3.40 \pm 0.67) \times 10^{-12}$	$(4.31 \pm 0.33) \times 10^{-12}$
3-year-aged	$(2.32 \pm 0.23) \times 10^{-12}$	$(2.50 \pm 0.09) \times 10^{-12}$

The samples with a seam showed air permeability constants higher than the respective samples without a seam, which was an indication of preferential paths for airflow through the seam region. The virgin sample with seam presented an air permeability constant of 34.5% higher than the respective sample without seam. The samples with a seam aged for 10 months and 3 years presented air permeability constants of 26.8 and 7.8% higher than those of the respective samples without a seam, respectively. The longer the aging time of the filter bag, the less pronounced was the difference between the values of the air permeability constants of the samples without and with seam, indicating that over time, the seam holes that were sealed by dust were no longer opened in the cleaning pulse and the filter bag with seam resembled the filter bag without seam.

Comparing the samples without seam, a reduction in air permeability of about 77% was observed in the filter bag aged for 10 months and 84% in the filter bag aged for 3 years, compared to the virgin sample. For the samples with seam, this reduction was around 78% and 87% for the filter bag aged for 10 months and 3 years, respectively, relative to the virgin sample. The pores of the aged samples were filled with dust, which contributed to the lower values of air permeability compared to the results of the virgin samples without and with seam.

3.3. Influence of Aging Time of P84 Filter Bags on Fractional Separation Efficiency. The fractional separation efficiencies of the virgin and 10-month-aged P84 filter media, without and with seam, are shown in Figure 10 for the particle size range from 0.5 to 2.8 μm. The results for the samples with 3 years of aging were not presented in the graph since the samples with 10 months of aging already showed a fractional separation efficiency of almost 100%.

The virgin sample without a seam in Figure 10 collected particles larger than 1.5 μm almost completely. For the smallest particles evaluated, it separated around 96% since for this particle size (0.5 μm) diffusion mechanism is already losing efficiency and impaction/interception is not yet as effective. The separation of larger particles by the fibers of the virgin sample without seam was favored by the intensification of interception and inertial impaction mechanisms.[15]

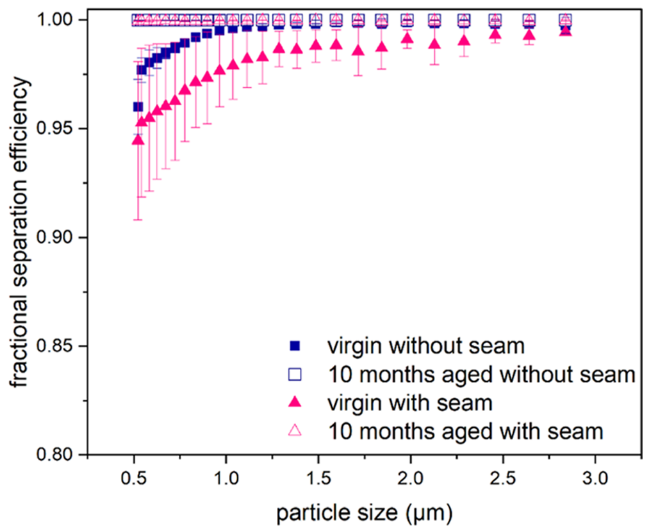

Figure 10. Fractional separation efficiencies of the virgin and 10-month-aged samples of P84 filter media without and with seam.

For the sample with the seam, the trend was the same as for the sample without the seam but with lower values, as some particles passed through the seam holes. The high deviations obtained were possibly related to the heterogeneity of the seam region, where there is the presence of the thread, seam holes, and overlapping fabrics. As presented in Table 4, the virgin sample with seam showed an air permeability constant of 34.5% higher than the sample without seam, which indicated lower airflow resistance and therefore resulted in lower separation efficiencies.

It is worth noting that the separation efficiencies of larger particles in the sample with seam were below 100%, because when there are preferential paths, the gas flow lines tend to mainly follow these paths and the interception mechanism may be impaired, since for a given particle size, there are certain gas flow lines that do not result in particle capture.[16]

Another point to highlight is that the sewing thread possibly negatively impacted the collection of particles. The greater thickness of the thread in relation to the fibers of the filter medium can hinder the collection of larger particles by the mechanisms that act in this diameter range since the interception and inertial impaction become less efficient for larger fiber sizes.[16]

The samples aged for 10 months, without and with seam, presented fractional efficiencies higher than 99.9% for the entire particle size range investigated, from 0.5 to 2.8 μm. These results indicated that after 10 months of use in the industrial bag filter, where the filter bag was subjected to filtration and cleaning cycles, the pores of the filter bag, as well as the seam holes, were sealed by the dust. The high separation efficiencies agree with the reduced permeabilities of the samples aged for 10 months, without and with seam (Table 4).

3.4. Influence of Aging Time of P84 Filter Bags on Filtration Cycles. Figure 11 shows the filtration cycles of the samples without and with seam of P84 filter media: virgin, 10-month-aged, and 3-year-aged. The room temperature during the cycles was 23.7 ± 2.5 °C, and the relative humidity was 26 ± 8%.

Considering the instability during the conditioning stage of the virgin samples, it can be said that the times to complete 30 cycles for the samples without and with seam, 900 and 887

https://doi.org/10.1021/acsomega.3c09037
ACS Omega 2024, 9, 10709−10716

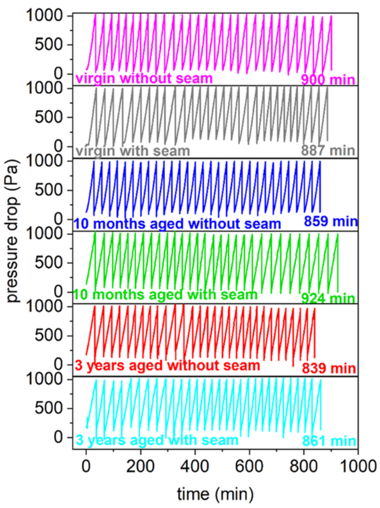

Figure 11. Filtration cycles of the P84 virgin sample without seam (pink), virgin with seam (gray), aged for 10 months without seam (blue), aged for 10 months with seam (green), aged for 3 years without seam (red), and aged for 3 years with seam (purple).

min, respectively, were very similar, with an average of only 26 s more in each cycle for the sample without seam. Evaluating the samples aged for 10 months (with and without seam), the sample with seam took 65 min longer to complete 30 cycles, an average of 2 min longer in each cycle. Comparing the samples aged for 3 years, the sample with seam also took longer to complete 30 cycles, 22 min in total, an average of 44 s longer per cycle. According to the aging time, the samples without and with seams became similar, as both the pores of the filter media and the seam holes were filled by dust. This greater similarity between the samples due to the aging time was also obtained in the permeability, according to Figure 9 and Table 4. In addition, it can be noted that the aging time of the filter bags had a greater influence on the samples with seam, since the difference between the time to complete 30 cycles of the samples with seam aged for 10 months and aged for 3 years (63 min) was approximately three times greater than the difference of the respective samples without seam (20 min).

4. CONCLUSIONS

This work investigated the influence of seam on the filtration performance of samples taken from P84 filter bags, collected from the sinter plant of a steel industry, at different stages of their service life. From the proposed objectives and the results presented, it can be concluded that

- the longer the time the filter bag has been in use, the less pronounced is the difference in the values of the air permeability constants of the samples without and with seam, which indicates that the seam holes are no longer reopened by the cleaning pulses;
- regarding the fractional separation efficiency, the time of use of the filter bags led to the closure of the pores and seam holes, so that the particles were collected with efficiency very close to 100% in samples with 10 months of use, without and with seam. For the virgin samples, there was a great difference in collection efficiency between the samples without and with seam because the seam holes became preferential paths;
- in the filtration tests in the VDI 3926 test rig, the results showed that the samples with seam took longer to complete the 30 cycles of the measurement phase. Over time of use, the samples without and with seam became more similar, as both the pores of the filter medium and the seam holes were filled with the powder. In addition, the aging time of the filter bags showed greater influence on the samples with seam, as the difference between the time to complete 30 cycles for the samples with seam with 10 months of use and with 3 years of use was approximately three times greater than the difference for the samples without seam.

In general, the results indicated that there is an influence of the seam on the filtration performance of the virgin filter bag, especially at the beginning of filtration. Some possibilities for reducing particle penetration through the seam region would be to carry out continuous injection of a precoat material to prevent the penetration of fine particles through the filter bags. Another alternative would be seams sealed with adhesive tape, which could improve the separation efficiency of the filter bag.

The experiments done by this study are a case-dependent study because the results are totally dependent on the type of filter bag and the powder used.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was financed by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior−Brasil (CAPES), Finance Code 001, grant no 88887.486170/2020-00; ArcelorMittal, grant no. 44/2015; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), grant no. 142086/2019−3; and Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), grant no. 97/04024−7.

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https://doi.org/10.1021/acsomega.3c09037
ACS Omega 2024, 9, 10709−10716