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Precoating Effects in Fine Steelmaking Dust Filtration

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Abstract: Particle emissions into the atmosphere can cause extensive damage to the environment and human health. To improve the efficiency in the collection of submicronic particles, new filtration media appeared on the market due to new textile technologies and equipment, such as filter media developed with polytetrafluoroethylene (PTFE) membranes; however, these are more expensive. A filter coating technique called precoating is a more economical alternative that could enhance filtration efficiency. This paper aimed to evaluate the operational parameters of precoating for micro- and nanoparticle filtration and compare the results with those obtained from the PTFE membrane. For this purpose, filtration cycles were performed, using precoated polyester with hydrated lime and dolomitic limestone, polyester with a PTFE membrane, and steel industry ultrafine dust. The results showed that the precoated polyester had a longer cycle duration and lower pressure drop than the polyester with a PTFE membrane. Therefore, precoating was shown to be a great alternative to be used in bag filters in steel mills because it presented high collection efficiency for submicronic particles, in addition to increasing the bag lifespan with less energy expenditure.

Keywords: precoating; filter media; bag filter; filtration; steelworks dust; high collection efficiency; low pressure drop

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1. Introduction

Air pollution with particulate matter affects 96% of the world's population. Rates of heart and respiratory diseases and lung cancer have increased and are responsible for the deaths of 4.2 million people [1]. When reduced particulate matter emissions are required, generally, fabrics with treatments are used, such as the polytetrafluoroethylene (PTFE) membrane. These treatments aim to reduce the penetration of fine particles and guarantee high collection efficiency (above 99.99%), providing a non-stick, high airflow solution that addresses these concerns [2]. However, these membrane filter media are extremely expensive compared with membrane-free filter media with simple surface treatments.

A more economical alternative is precoated filters, which are already used by many industries. Precoating consists of coating the surface of non-woven filter media with particulate material, forming an initial cake, preventing particle penetration on the filter media causing its saturation (clogging) [3]. Precoating is responsible for the cake formation; in other words, the cake works as a filtration element improving collection efficiency and minimizing clogging. The clogging of the porous filter media is accompanied by a pressure drop that necessitates constant cleaning, changing of filtration bags, and high energy consumption. Precoating allows air to flow freely through the filter media and decreases adhesion between the cake and fibers facilitating the cleaning of the bags, resulting in an extended life span [4,5].

There are few articles that discuss precoating in gas filtration, especially related to industrial operating conditions in the steel industry. Ravert [5] concluded that precoating improved the air flow in the filter medium and increased the service life of bag filters.

Li et al. [6], associated with the Höflinger group, analyzed the influence of operating parameters on a precoat (diatomite) layer under crossflow conditions and concluded that the filtrate flux decreased with increasing crossflow velocity and decreasing aid concentration filter. Schiller and Schmidt [3] presented a study using eleven filters and three precoat dusts (limestone dust, hydrated limestone, and iFIL coating N®) during ultrafine particle filtration in a pellet heater the authors analyzed the best combinations between filter media and precoating dusts, and concluded that the filter medium PTFE + PI filter showed the best performance. Schiller et al. [7] compared the collection efficiency values in precoat reuse (hydrated limestone) in a laboratory plant and in a real pellet heater plant. The authors observed that there was a linear increase in collection efficiency with precoat reuse in the laboratory plant, but in the real plant, values did not present linearity and a comparison was not possible.

Khirouni et al. [8] investigated precoating for improving pulse-jet cleaning of flat filters clogged with metallic nanoparticles. Parameters such as cleaning air pressure, filtration velocity, and deposited mass of precoating were evaluated. They concluded that precoating improved cleaning efficiency with a regeneration efficiency 75% higher than filter media without precoating. It also increased the collected mass of nanoparticles, reduced cleaning air pressure, and increased filtration velocity.

Due to the limited studies reported in the literature regarding the use of fabric filter precoating, especially for those applied in steel industries, and considering the higher costs of using filter media with PTFE membranes when high collection efficiencies are required, this paper aims to determine the most appropriate precoating parameters to be used as a cost-effective alternative to polyester with PTFE membrane. For this purpose, the following parameters were evaluated: precoat dust, precoat mixtures, precoating maximum pressure drop, micro and nanometric particles collection efficiency, filtration cycle duration, residual pressure drop, and filter residual mass after air pulse jet cleaning. The following filter media were used: polyester, polyester with precoating layers, and polyester with PTFE membrane.

2. Materials and Methods

2.1. Particulate Matter Characterization

In the experimental tests, hydrated lime and dolomitic limestone were used as the precoating dust and steel mill dust in the filtration. Different mixtures were also used between hydrated lime and steelmaking dust, and between dolomitic limestone and steelmaking dust as precoating. In this stage, several experiments were carried out with different thicknesses of precoating, that is, different pressure drop limits. Table 1 and Figure 1 provide the results obtained for the characterization of dusts. The dust densities were measured by helium pycnometry with AccuPyc 1330 Micrometrics equipment, in triplicates. For each dust mean, aerodynamic diameters for powder and mixtures were obtained in the Aerodynamic Particle Spectrometer model TSI 3320 and through SEM images (MAGELAN 400 L) (see Figure 1). The chemical elements of the dusts used were determined on an X-ray fluorescence spectrometer and for direct combustion; the results are listed in Table 2.

2.2. Filter Media

For the filtration tests, the following filter media were used: polyester 540 and 550 g/cm^2 (PE 540, PE 550), PTFE membrane polyester 550 g/cm^2 (PE + PTFE), and polyester with Primashield (fluoro carbon treatment) of 540 and 600/cm^2 (PE P 540 and PE P 600). Table 3 presents the results obtained from the characterization of filter media used in this study, including: average fiber diameter, air permeability, and porosity. Scanning electron microscopy (SEM) images and Image Pro Plus (7.0) software were used to determine the average filter media fiber diameter, according to Bortolassi et al. [9]. Filter media permeability and porosity were acquired by varying the flow of clean air through the filter medium, in the equipment shown in Figure 2.

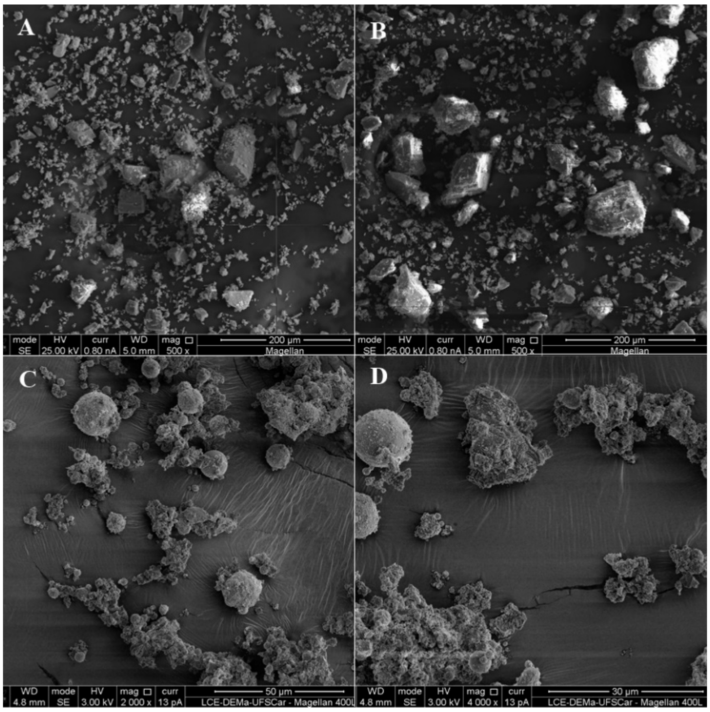

Figure 1. SEM images of particulate matter: (**A**) hydrated lime; (**B**) dolomitic limestone; and (**C**,**D**) steelmaking powder.

Table 1. Characterization of precoat materials.

Precoat Materials	Specific Mass (g/cm^3)	Mean Aerodynamic Diameter (μm)
Steelmaking powder	3.4179	3.92
Hydrated lime (1:0)	2.7742	3.22
Hydrated lime/Steelmaking powder		
(1:9)	2.9092	12.30
(3:7)	2.8355	0.68
(1:1)	2.8492	13.70
Dolomitic limestone (1:0)	2.8222	3.04
Dolomitic limestone/Steelmaking powder		
(1:9)	2.8851	2.74
(3:7)	2.8654	13.90
(1:1)	2.8671	13.40

Table 2. Chemical elements of particulate matter.

	Ca%	Mg%	Si%	Fe%	Al%	C%	CaO%	Fe_2O_3%	Al_2O_3%	SiO_2%
Hydrated lime	89.9	6.5	2.5	0.4	0.3					
Dolomitic limestone	76.9	13.6	3.1	2.6	1.8					
Steelmaking powder						2.8	51.2	43.2	1.9	0.8

Table 3. Characterization of filter media.

Filter Media	Mean Fiber Diameter (μm)	Air Permeability at 125 Pa (m^3/min/m^2)	Porosity
PE + PTFE	5.10 ± 5.7	3.8	0.515
PE 540	13.8 ± 3.5	10.6	0.874
PE P 540	13.9 ± 2.2	10.2	0.856
PE P 600	16.2 ± 2.2	12	0.876
PE 550	14.9 ± 3.9	21.8	0.883

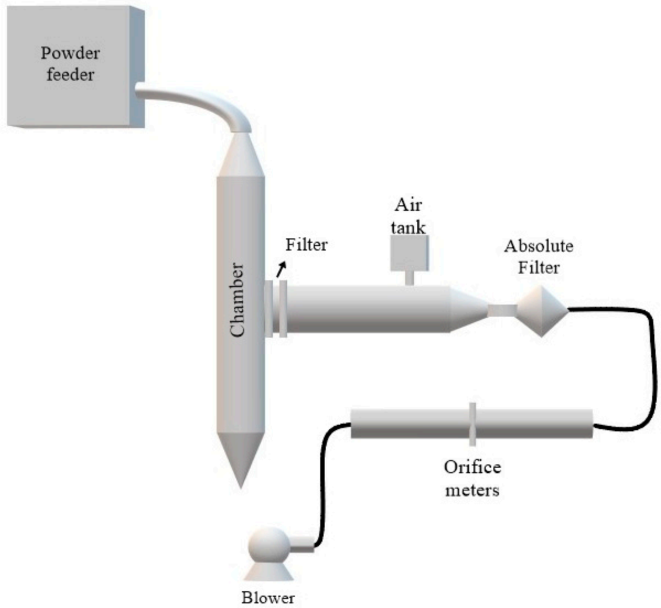

Figure 2. Schematic view of the filtration equipment.

2.3. Experimental Conditions

The equipment used for the filtration cycle experiments was built based on the VDI 3926 standard, which simulates an industrial bag filter in a laboratory scale (see Figure 2). Filtration equipment consisted of a chamber, vertical tube with a diameter of 19.5 cm and height of 104 cm, and a horizontal tube with a diameter of 16 cm and height of 84 cm. The filter medium sample position was between the vertical and horizontal tubes, followed by an absolute filter (used polypropylene–PP in all filtration tests).

The air fed into the system originated from a compressed air line, passed into a silica column to remove humidity, and then entered a dust feeder. The particulate material was fed in a rotating plate and sucked by a venturi tube that formed aerosol and dispersed it into the chamber that led to the filter media. An exhaust fan promoted air suction in the system. The particles that passed through the filter medium were collected in the absolute filter located downstream.

Filtration tests were carried out, keeping the operational parameters constant within the ranges typically used in the VDI 3926 standard: 2 m/min filtration velocity; 1000 Pa maximum pressure drop (ΔPmax); 60 ms cleaning pulse jet time; and 5 bar pressure. The filtration surface was 20,106 cm^2 with a 40 L/min volume flow, 2 m/min air-to-cloth ratio, and 5000 mg/m^3 dust concentration. The number of filtration cycles was established at 30, which were carried out in triplicates. The local experimental conditions of the air temperature and humidity were at 25 °C and less than 50%, respectively.

2.4. Collection Efficiency for Micrometrics Particles

To determine the filter media efficiency for particles smaller than 10 μm (PM10), the experimental unit APS (Aerodynamic Particle Sizer spectrometer) was used (see Figure 3). The unit was composed of a particle feeder (model 3433, TSI), diluter (model 3302A, TSI), aerodynamic particle sizer spectrometer (model 3320, TSI), flowmeter (Gilmont), and pump.

The dust that was used in the particle feeder (model 3433, TSI) was from a steelmaking shop, with 3.4179 ± 0.0043 g/cm^3 particle density and 3.92 ± 0.12 μm aerodynamic mean diameter. Isokinetic samplings were performed upstream and downstream from the filter medium (PE 540, PE 550, PE + PTFE 550, PE P 540, and PE P 600), in triplicate. The filtration area was 17.57 cm^2 (4.73 cm of diameter) and it was operated with a 2 m/min superficial gas velocity (air to cloth ratio), which was the same as that used by the VDI 3926; this value was standardized for all filtration tests.

The collection efficiency, which represents the fraction of particles retained by the filter medium, was determined using the following equation:

$$E = \frac{C_0 - C_1}{C_0} \quad (1)$$

where E is the collection efficiency, C_0 is the particle concentration before, and C_1 is the particle concentration after the filter media [10].

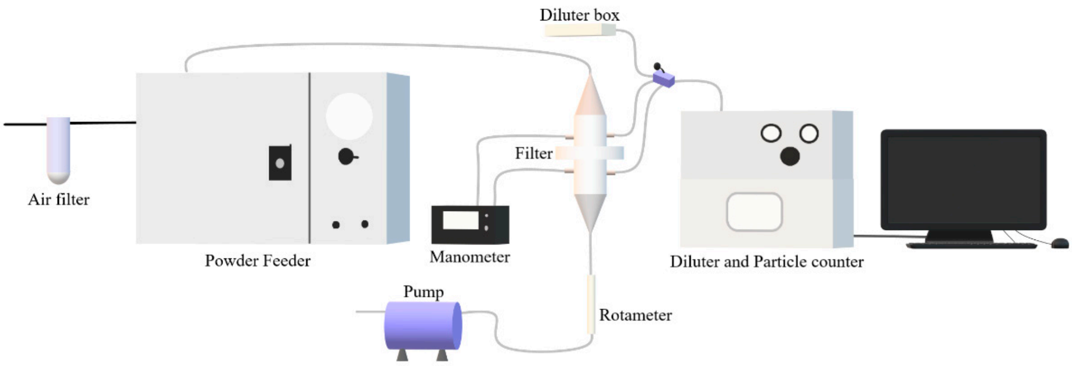

Figure 3. Schematic view of the APS unit.

2.5. Collection Efficiency for Nanometric Particles

To determine filter media efficiency for nanoparticles, the SMPS unit apparatus (see Figure 4) was used, consisting of an aerosol generator (Model 3079, TSI), filtered air supply (Model 3074B, TSI), diffusion dryer (Model 3062, TSI), krypton-85 charge neutralizer (Model 3054, TSI), filter media apparatus, americium-241 charge neutralizer, flowmeter (Gilmont) and scanning mobility particle sizer (SMPS) composed of an electrostatic classifier (Model 3080, TSI), differential mobility analyzer, and particle counter (Model 3776, TSI). Nanoparticles (7.64 to 278.8 nm) were generated by the aerosol generator from a 0.1 g/L NaCl solution. In SMPS, isokinetic samplings were performed upstream and downstream from the filter media (PE 540, PE 550, PE + PTFE 550, PE P 540, and PE P 600), which recorded the concentration of nanometric particles by electric mobility diameter. The superficial velocity (air–cloth ratio) was 2 m/min, which was the same applied to all experiments of this study. Each collection efficiency test was performed in 5 min and done in triplicate.

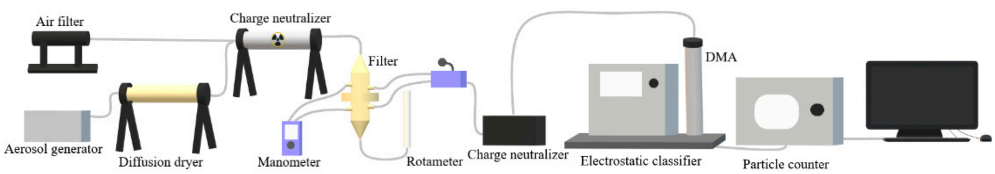

Figure 4. Schematic view of the SMPS unit.

2.6. Evaluation of Precoating with Best Performance

To evaluate precoating performance during air filtration, the maximum precoating pressure drop and precoat mass fed were varied to investigate their influence on collection efficiency. The following subtopics describes the details of those tests.

2.6.1. Influence of Maximum Pressure Drop from Precoating on Filtration Efficiency

Hydrated lime and dolomitic limestone were used to precoat polyester (PE 550) filter media in the filtration unit (Figure 2). For each precoat dust, the experiments were conducted maintaining the filtration velocity at 2 m/min until it reached the predetermined precoating pressure drop of 100, 200, 300, and 400 Pa; in other words, were used different precoating thicknesses (amount of mass per area). Collection efficiency was measured for each pre-established pressure drop value.

Thus, after reaching the precoating maximum pressure drop value, the filter media were taken to the APS experimental unit (Figure 3) and the collection efficiency of the microparticles was measured using the steelmaking dust to simulate filtration.

2.6.2. Precoat Dust Mixing Ratio and Its Influence on Filtration Efficiency

These experiments were carried out to verify the influence of precoating dust (hydrated lime and dolomitic limestone) when mixed with the steelmaking dust on the performance of the bag filter during air filtration. Different mixtures of these dusts were prepared 1:0, 1:1, 3:7, and 1:9 (see Table 3). The tests were performed in an APS experimental unit (Figure 3), and the filter medium used was polyester (PE) because it has low costs and is widely used in the industry. A 200 Pa precoating maximum pressure drop was established to obtain the collection efficiency for microparticles because it was the clogging point observed in precoating tests.

2.7. Filtration Cycles

The filtration cycles were performed in the experimental apparatus shown in Figure 2, where it was possible to perform 30 filtration cycles in duplicate, for each experimental condition previously established. These filtration tests and cleaning of the filter media (bag) were carried out following the operational conditions suggested by the VDI 3926 standard and using steelwork dust as the particulate material to be filtered at a concentration of 5 g/m^3, at a surface filtration velocity of 2 m/min and maximum pressure drop of 1000 Pa. Polyester (PE) and polyester with PTFE membrane (polytetrafluoroethylene) filter media were used to verify the filtration curves, operated under the same experimental conditions when performed with precoating (PE), non-precoating (PE), and non-precoating (PTFE) fabrics. For experiments using the polyester filter medium, the filtration was first started by feeding the system with the precoating dust, until reaching the 200 Pa pressure drop. This procedure was only performed for the first filtration cycle. Then, with the precoated filter medium (PE), filtration was continued, now with the steelmaking dust, until a 1000 Pa maximum pressure drop value was reached, after which the pulse jet cleaning was started. Soon after cleaning, a new cycle started until all 30 filtration cycles were carried out.

For better understanding of the 30 filtration cycles, Curve 1 and Curve 2 (duplicate) depicts the filtrations performed using the hydrated lime dust precoating, and Curve 3 and Curve 4 (duplicate) for the filtrations using the dolomitic limestone dust for precoating.

2.8. Particle Penetration in the Filter Media

After reaching 30 filtration cycles, the filter media were prepared according to the methodology of Aguiar and Coury [11], where an adhesive was percolated through the cake. Then, the fabric containing the cake was placed over polyurethane foam soaked in resin and taken to the oven. After being dried, the cake was cut into small squares and cast in a thermoset resin. Then, it was polished according to standard procedures for microscopic examination to obtain the filter medium cross-section scanning electron microscope (SEM) images with the residual dust mass. To facilitate SEM image analysis, they were binarized using image Pro Plus 7.0 software; thus, the filter medium particle penetration and fiber-retained particle quantity were determined.

3. Results

3.1. Micrometric Particle Collection Efficiency

The collection efficiency data for micrometer particles (0.523 to 10 μm) obtained from the APS unit (item 2.5) for all filter media without precoating can be seen in Figure 5.

Filter media without the surface treatment, PE 540 and PE 550, presented lower microparticle collection efficiencies. On the other hand, filters with PTFE treatment improved microparticles collection efficiency. This behavior was also observed in Figure 5 for the PE P 600, PE P 540, and PE + PTFE filter media.

The filter medium PE 540 showed higher efficiency than PE 550. As expected, PE P 600 presented higher collection efficiency than PE P 540 because it presented a higher grammature.

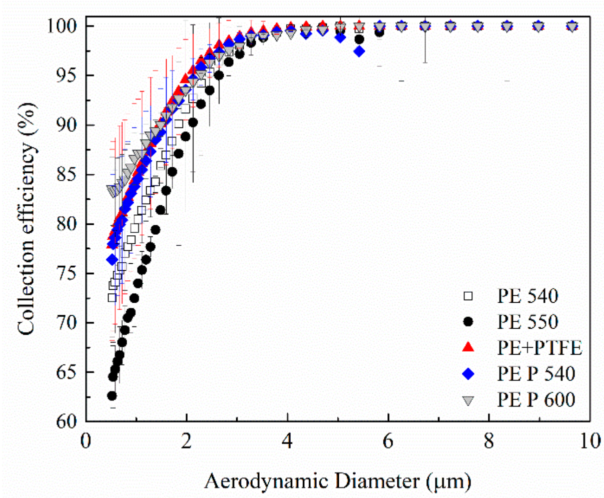

Figure 5. Collection efficiency of micrometric particles.

3.2. Nanometric Particle Collection Efficiency

Nanometer particle concentration and collection efficiency curves obtained in the scanning mobility particle sizer (SMPS) in the range of 7.64 to 278.8 nm are presented in Figure 6. The aerosol presented at higher concentrations over 50 nm.

PE + PTFE presented efficiencies above 95% for almost the entire diameter range, whereas, for other filter media, there was a decrease in collection efficiency as diameter increased. This decrease in nanometric particle collection efficiency, in contrast to collection efficiency of micrometric particles in Figure 5, occurred because the nanometric diameter range is a MPPS area [12], where the interception and impaction mechanisms are inefficient and require a PTFE membrane that forms a porous surface, with smaller diameter fibers that assist in particle capture.

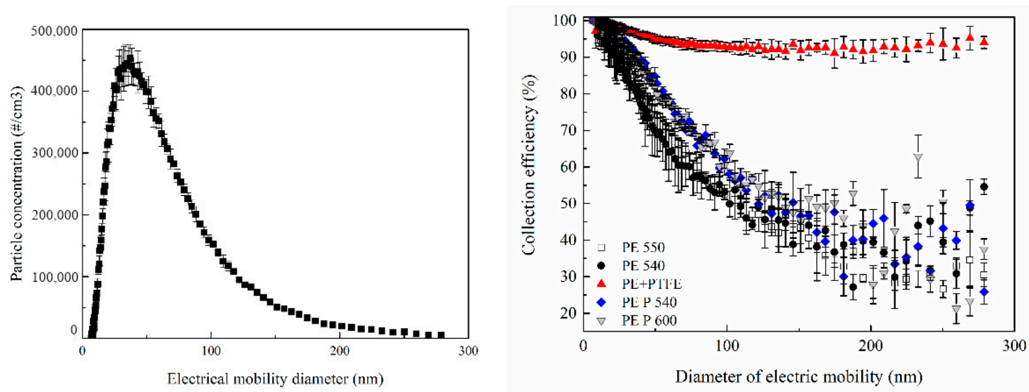

Figure 6. Collection efficiency of nanometric particles.

3.3. Maximum Precoating Pressure Drop

The filter medium used for the precoating tests was PE 550. It was selected because it is one of the most used in the steel industries, due to its efficiency, strength and relatively low pressure drop value (30 Pa). The precoating experiments were carried out in triplicate in filtration equipment shown in Figure 3 (item 2.4), whose maximum filtration pressure drop value for precoating powders ranged from 100, 200, 300, and 400 Pa, representing an increase in precoating layer thickness at each respective maximum pressure drop values. The particulate material used in the precoating were hydrated lime and dolomitic limestone.

The experimental efficiency data obtained for each precoat maximum pressure drop value were compared with each other and with the efficiency data obtained for the clean filter media (without the precoating). These results are shown in

It can be seen in Figure 7 that the clean PE 550 had low microparticle collection efficiency, below 85% (PM4). As the precoating layer was formed, the collection efficiency increased and above the maximum pressure drop of 200 Pa reached a value very close to 100% for the entire investigated diameter range (from 0 to 18 microns). This was also found for the other maximum pressure drop values of 300 and 400 Pa. The hydrated lime precoating layer was less efficient than the dolomitic limestone layer under the same operating conditions for the 100 Pa pressure drop.

Comparing the collection efficiency results for both cases of precoating with the PTFE membrane in Figure 7, it is observed that the precoat layer improved microparticle collection efficiency, especially for particles smaller than 3 μm not requiring a large precoating thickness to achieve efficiencies close to 100%. Figure 7.

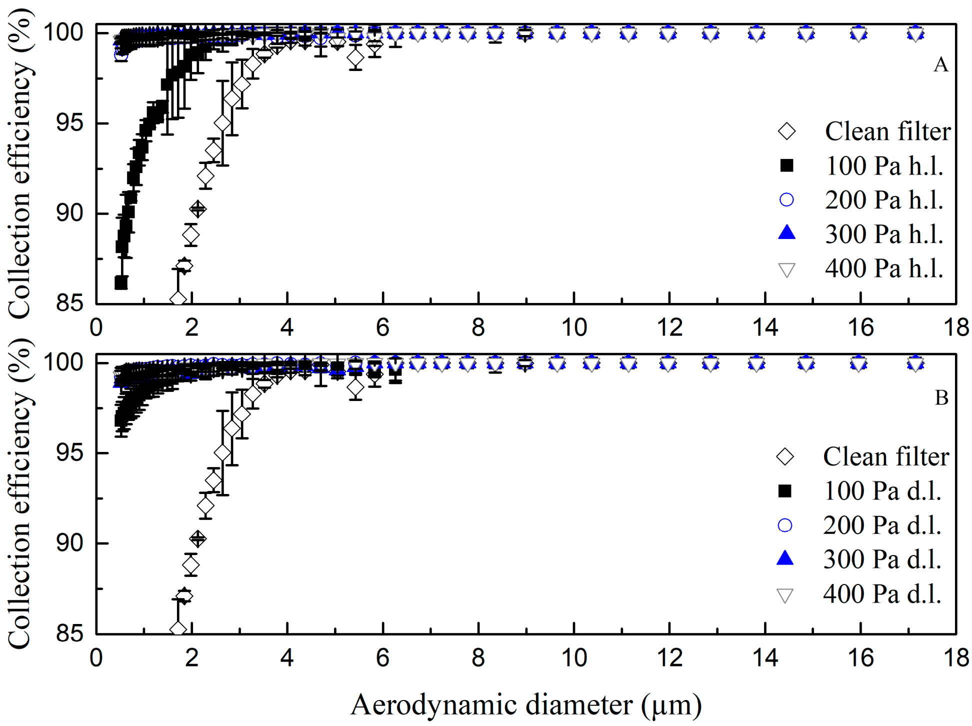

Figure 7. Collection efficiency by varying maximum pressure drop: (**A**) hydrated lime (h.l.) and (**B**) dolomitic limestone (d.l.) [13].

3.4. Influence of Precoat Mixing Ratio on Filtration Efficiency

As the microparticle collection efficiency was very close to 100% for the 200 Pa maximum pressure drop (see Figure 7), this value was chosen to represent the ideal precoating layer thickness. Thus, for these tests, the precoating powder was filtered until reaching the 200 Pa maximum pressure drop value, as shown in Figure 8. Polyester filter media (PE 550) and powder mixtures were used for precoating, as shown in Table 3, to form the precoating layers. Figure 8 shows the microparticle collection efficiency curves varying the aerodynamic diameter for each precoat mixture used.

Particle collection efficiency results obtained for the mixtures using hydrated lime powder for the precoating were similar. Nearly all curves reached very close to 100% efficiency for the entire collected particle diameter range. When dolomitic limestone powder mixtures were used for precoating, the collection efficiency was lower for the 7 micron particle size range (PM7).

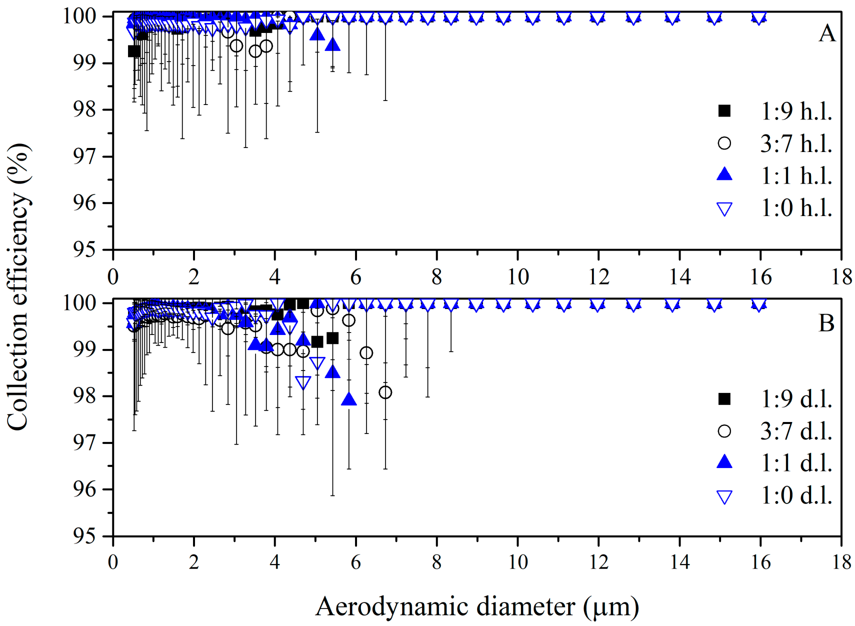

Figure 8. Collection efficiency by varying mixing ratio: (**A**) hydrated lime (h.l.) and (**B**) dolomitic limestone (d.l.).

To compare filter media performance in different conditions, we analyzed the collection efficiency as a function of aerodynamic diameter for clean polyester (PE 550), polyester (PE 550) with precoating layers of hydrated lime (1:0) and dolomitic limestone (1:0), and polyester with PTFE membrane (PE + PTFE), as shown in Figure 9. This mixing ratio was chosen to analyze the influence of pure powder on collection efficiencies. All curves presented error under 1%.

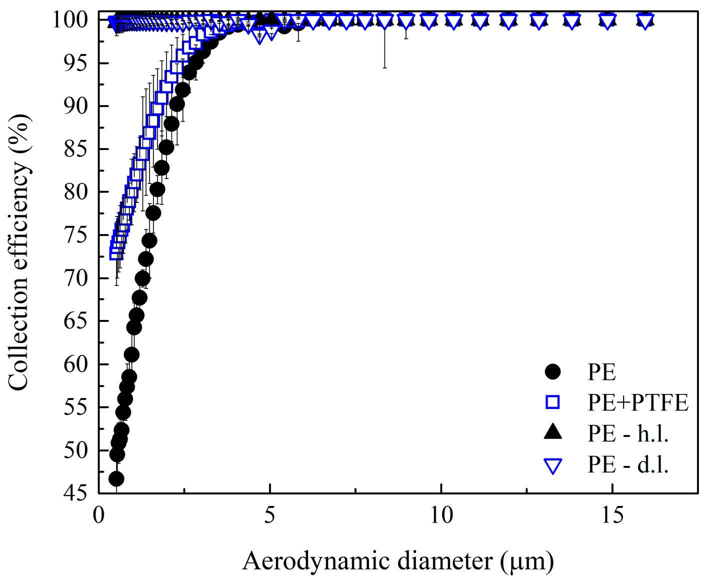

Figure 9. Collection efficiency of micrometric particles in polyester (PE), polyester with PTFE membrane (PE + PTFE) without precoating, polyester with hydrated lime precoat layer (PE-h.l.), and polyester with dolomitic limestone precoat layer (PE-d.l.).

Without precoating, the collection efficiencies of PE 550 and PE + PTFE were below 95% to PM 2,5; after precoating, the collection efficiency of polyester (PE) was above 99% for all diameter ranges. This indicated the precoating effectiveness for smaller particles as PM 5.

3.5. Filtration Cycles

Figure 10 shows 30 filtration cycle curves (pressure drop as a function of time). To carry out these 30 cycles, the following were used: used dust from the steel industry, which fed the filtration system; two filter media, PE and PE + PTFE; and PE filter media precoated with hydrated lime (1:0) and dolomitic limestone (1:0) powders. The maximum precoating pressure drop used was 200 Pa (Table 4), because in previous tests (item 3.3), the efficiencies at this pressure drop were close to 100%.

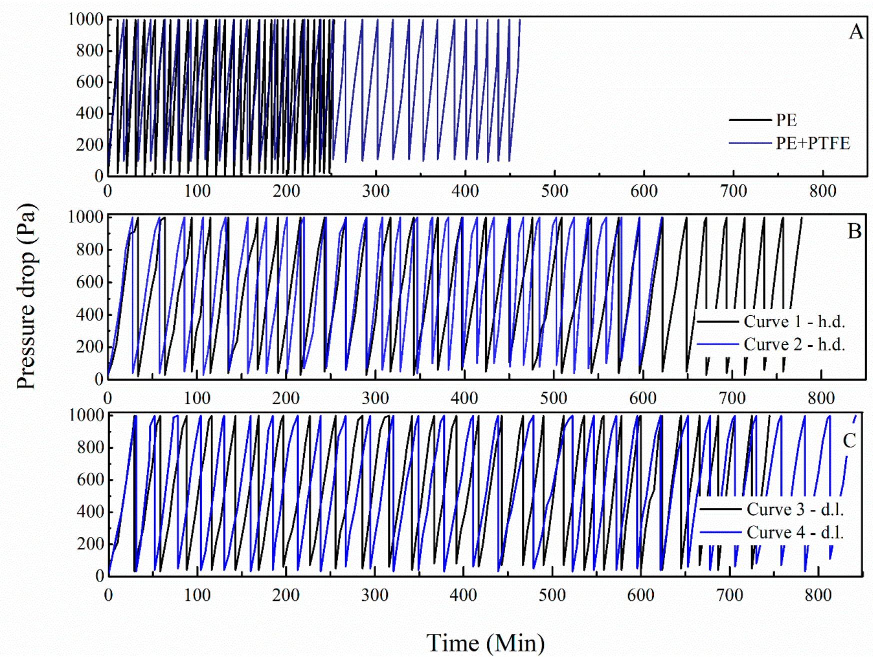

Figure 10. Pressure drop curves for: (**A**) clean PE and PE + PTFE, (**B**) PE precoated with hydrated lime, and (**C**) PE precoated with dolomitic limestone.

Table 4. Filtration cycle experiments.

Filter Medium	Filtration Cycles	Precoat	ΔP Precoat (Pa)	Porosity	Thickness
Polyester (PE)	30	-	-		
Polyester PTFE membrane (PE + PTFE)	30	-	-		
Polyester (PE)	30	Hydrated Lime	200	0.827	0.383
Polyester (PE)	30	Dolomitic Limestone	200	0.833	0.315

Due to the PTFE membrane in the PE + PTFE filter medium, the duration of 30 filtration cycles was 208 min longer than the 30 filtration cycles using clean PE 550 (see Table 5).

Table 5. Duration and collection efficiencies of filtration curves.

Filter Medium	Residual Pressure Drop (Pa)	Duration of 30 Cycles (min)	Collection Efficiency (%)
PE	20	253	99.6544
PE + PTFE	110	461	99.9908
PE-hydrated lime (Curve 1)	40	778	99.9869
PE-hydrated lime (Curve 2)	50	621	99.9929
PE–dolomitic limestone (Curve 3)	50	775	99.9900
PE–dolomitic limestone (Curve 4)	50	842	99.8535

For precoated filter media, for both precoat powders, the average duration of 30 filtration cycles was 300 min longer (Curves 1, 3, and 4; Figure 10B,C) than PE + PTFE cycles.

For PE 550, the 30 cycle durations were approximately half the duration of precoated filter media.

The residual pressure drop for PE + PTFE stabilized at 110 and 50 Pa for precoated PE 550 filters. Thus, precoating residual pressure drop was lower than polyester with PTFE membrane, which explains the longer duration of the filter and consequently reduced energy consumption costs.

However, due to filtration system sensitivity, no clear conclusions could be drawn about which precoat powder had the best filtration performance. The results suggest that, after 30 cycles, the precoated filters showed slightly higher efficiencies than the PTFE membrane filter media (see Table 5).

Due to the irregularities in fiber distribution, permeability, and porosity of the filter media samples, even if they were from the same batch of fabric (see Table 3), and due to differences in the environment, such as temperature and humidity, and the sensitivity present in the filtration system resulted in curves for duplicates with different behaviors.

The residual pressure drop curves for the 30 filtration cycles can be seen in Figure 11. Note that both the PE550 and PE + PTFE filter media presented residual pressure drop variation between 10 and 20 Pa. On the other hand, the filter media precoated with hydrated lime and dolomitic limestone powders showed much greater variation in residual pressure drop. Furthermore, the variation for the filter media precoated with hydrated lime powder was between 30 and 90 Pa, and for those precoated with dolomitic limestone powder, the variation was a little higher, between 20 and 110 Pa, indicating irregular cleaning during the 30 filtration cycles.

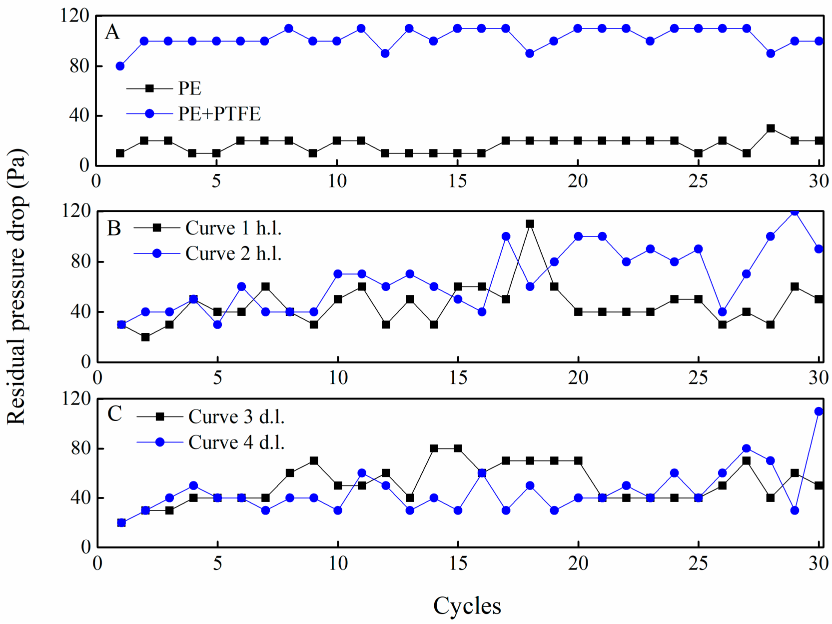

Figure 11. Residual pressure drop after 30 cycles: (**A**) PE and PE + PTFE, (**B**) PE precoated with hydrated lime, and (**C**) PE precoated with dolomitic limestone.

3.6. Particle Penetration in the Filter Media

After the binarization of SEM images, it was possible to count the number of particles that penetrated the filter media (see Figure 12).

Comparing the PE with the PE + PTFE membrane, the innermost fibers of the PE were greater and there was a small reduction in the particles deposited on the fibers along their thickness (thickness of 0 to 1940 µm), with between 700 and 600 particles. The PE + PTFE membrane hindered particle deposition in its innermost fibers, obtaining 600 particles deposited from the filter medium/cake interface up to a 485 µm depth and approximately 100 particles to a 1940 µm depth (1.94 mm). Therefore, the filter medium with the membrane reduced particle penetration by 84% compared with the PE 550 filter medium.

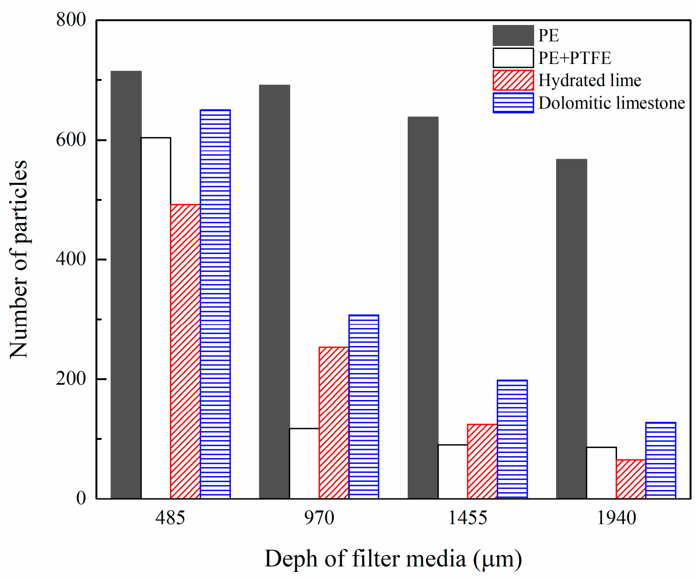

Figure 12. Particle penetration in filter media.

Comparing the hydrated lime powder precoated filter medium to the PE + PTFE filter medium, the number of particles deposited from the filter medium/cake interface up to a thickness of 485 µm was much smaller for the precoated filter than the number of particles deposited in the PE + PTFE. However, the particle deposition in the innermost layers along its thickness was decreasing, presenting a slightly greater number of particles than the PE + PTFE, and for the 1940 µm depth, the amount of particles deposited was a little less when compared with PE + PTFE, with 3.7% difference. It was also verified that the PE 550 filter medium without the precoating had a much higher particle deposition, with a difference of approximately 700 more particles than the PE 550 with powder hydrated lime precoating, at a 1940 µm depth. Thus, the hydrated lime precoat prevented particle penetration along the thickness by 88% compared with the PE 550 without precoat.

The number of particles deposited along the thickness of the fibers of the PE 550 filter medium precoated with dolomitic limestone powder was 11% higher than in the PE 550 filter medium precoated with hydrated lime powder. This difference explains the longer filtration cycle time for PE 550 precoated with dolomitic limestone in comparison with the filtration cycle time for the PE 550 precoated with hydrated lime. This filter medium presented with 77% fewer deposited particles, at a 1940 µm depth, than in the PE 550 filter medium without precoating, and only 7% more than in the PE + PTFE filter medium. After 30 filtration cycles, the collected mass in the absolute filter after passing through the filter media was 0.3151 g for the PE 550 filter media without precoating, 0.1272 g (Figure 10B, Curve 1) and 0.0984 g (Figure 10B, Curve 2) for the PE 550 filter medium with hydrated lime precoat, and 0.0924 g (Figure 10C, Curve 3) and 0.9677 g (Figure 10C, Curve 4) for filter media precoated with dolomitic limestone.

4. Discussion

4.1. Micrometric Particle Collection Efficiency

Air filtration in fabric filters occurs with dust cake formation, which is trapped in the innermost fibers and/or on the filter medium surface. For filter media without surface treatment, the filtration process is generally longer and may result in lower microparticle collection efficiencies. This behavior can be seen in the PE 540 and PE 550 filters (without treatment), as shown in Figure 5, that represents the micrometric particle (0.523 to 10 µm) collection efficiency data obtained from the APS unit (item 2.5) for all filter media without precoating. For filters with PTFE treatment, the cake was formed from the first filtration cycle on the filter medium surface without the particles interacting with the filter medium innermost fibers. Filter media surface treatments aim to improve the microparticle collection efficiency. The same was observed for the PE P 600, PE P 540, and PE + PTFE filter media.

The filter medium with PTFE treatment had the highest collection efficiencies, mainly for ultrafine particles. The filter medium PE 540 showed higher efficiency than PE 550 because of its lower porosity and permeability due to the smaller fiber diameter (see Table 3), meaning that the filter medium has smaller interstices that result in greater collection efficiency, mainly at the beginning of the filtration when the cake has not formed yet. Similarly, due to its higher grammature, PE P 600 had a higher collection efficiency than PE P 540.

4.2. Nanometric Particle Collection Efficiency

The filter media collection efficiency curves for nanometric particle collection efficiency (Figure 6) could be correlated with the filtration mechanisms studied by Hinds [12], which describe that filter efficiency is a function of particle and fiber size.

Depending on the particle and fiber sizes, one filtration mechanism becomes more effective than another. Hinds (1982) [12] showed that for particle sizes between 100 and 400 nm, the filter medium total efficiency decreases, as the filter mechanism is ineffective for this diameter size range; the diffusion mechanism influence also had a collection efficiency that was reduced for the larger particle diameter. The opposite occurred with the interception mechanism that became more effective as the particle grew. Thus, both diffusion and interception mechanisms had a greater influence on this diameter size range, which corresponded to the most penetrating particle size (MPPS) or minimal efficiency regions, where for particles whose diameter is smaller than MPPS, there was a predominance of diffusion mechanism, and for particles with a larger size, the interception mechanism predominated [14]. This explains the collection efficiency decrease as the particle diameter increases for all polyester filter media except for PE + PTFE. For micrometrics particles, the collection efficiency increased because particle diameters were large enough to facilitate the capture.

4.3. Maximum Precoating Pressure Drop

As the precoating layer was formed, probably at a pressure drop of 200 Pa for the PE 550, the collection efficiency increased. This was because the clogging point (the point at which the filter media is saturated with dust and particle collection starts to occur among the particles and no longer between the particles and filter media fibers) had been achieved. This improved the microparticle collection efficiency, especially for particles smaller than 3 µm, not requiring a large precoating thickness to achieve efficiencies close to 100%. This behavior was also verified by Andrade et al. (2019) [13]. and Schiller and Schmid (2014) [3].

As mentioned before, the dolomitic limestone precoating layer showed a better efficiency for the 100 Pa maximum pressure drop than for the hydrated lime layer precoating. This was because the PE 550 clogging point with dolomitic lime powder was reached 52 s earlier than with hydrated lime powder, with 201 mg less deposited powder mass. In this case, the particle size influenced the precoating powder layer formation in the PTFE 550. The dolomitic limestone powder has a smaller average aerodynamic diameter (see Table 1), which caused the powder particles to deposit in the more internal parts of the filter medium, clogging pores and consequently increasing air flow resistance. This raised the pressure drop value faster, forming a more compact precoating layer with the clogging point being reached in less time and with lesser amounts of powder mass deposited on the filter medium. The hydrated lime powder, on the other hand, due to its larger average aerodynamic diameter, did not allow large amounts of dust to penetrate the filter medium internal pores, resulting in greater particle deposition on the filter media surface, forming a more porous precoating layer, thus reducing resistance to the passage of air. Consequently, there was a slower increase in the pressure drop, which led to greater particle deposition. This behavior was verified in the initial stages of [15,16].

4.4. Influence of Precoat Mixing Ratio on Filtration Efficiency

The drop in collection efficiency for particles from 2.5 to 7 μm could be explained due to collection mechanism effects, interception, impaction, and gravitational effect, which is becoming more effective for particles larger than 2 μm [12,13]. The improvement for collection efficiencies to PM 2.5 indicates the effectiveness of precoating for smaller particles such as PM 5, due its lower porosity.

4.5. Filtration Cycles

The duration of 30 filtration cycles for the PE + PTFE filter medium was longer than the 30 filtration cycles using clean PE 550 (see Table 5 and Figure 10). This occurred because the PE presented with greater cake compaction and greater pore obstruction due to its higher porosity (0.883 porosity for PE and 0.515 for PE + PTFE) and the rapid increase in pressure drop resulting in shorter filtration cycles. It was observed that the PE + PTFE presented very similar behavior during the 24 filtration cycles.

For precoated filter media, the average duration of 30 filtration cycles was longer than PE + PTFE cycles and PE 550 because the precoating had improved filtration performance by increasing cycle duration and maintaining lower pressure drop compared with the PTFE membrane. The clean PE 550 filter, due to its greater air permeability and porosity, presented with lower performance than the PE + PTFE filter medium (see Table 3). This way, the precoating layer deposited on the PE 550 surface improved its performance, making the filtration cycles longer due to its slower increase in pressure drop.

The precoating residual pressure drop was lower than for the polyester with PTFE membrane, which explains why the precoating filter lasts longer and had reduced energy consumption costs.

After 30 cycles, the precoated filters showed slightly higher efficiencies than the PTFE membrane filter media (see Table 5) because the filter media with precoating had a lower cost and presented a longer cycle duration, resulting in a longer useful life and the lower number of cleanings needed in the same time period. Schiller (2014) [3] described that the ideal combination of filter media and precoat material should have high total collection efficiencies for the finest powder and a low pressure drop, confirming the results obtained in this study.

Analyzing the particle penetration for filters precoated with hydrated lime, Curve 1 shows a larger particle penetration into the filter medium compared with Curve 2, resulting in a longer internal filtration period. In the first cycle, 778 mg of powder were deposited in the filter medium, whereas in the other cycles, the deposition was 670 mg. This led to the formation of a less porous cake, increasing the total filtration time for the thirty cycles in relation to the first cycle of the duplicate. This deposited a smaller number of particles in the internal fibers of the filter media, forming a more compact cake on the surface of the filter medium, making it difficult to remove the cake, which led to lower cycle duration for the thirty cycles. For dolomitic limestone, almost the same mass of powder was deposited throughout the filtration period, but Curve 4 was longer than Curve 3.

Both the PE550 and PE + PTFE filter media presented residual pressure drop variation between 10 and 20 Pa (Figure 11). On the other hand, the filter media precoated with hydrated lime and dolomitic limestone powders showed much greater variations in residual pressure drop. This happened because, during reverse pulse cleaning, some precoat pieces may have been removed from patchy cleaning of the filter media, leaving some filter medium areas cleaner and reducing the residual pressure drop. In the next filtration cycle, after cleaning, the fluid tends to flow through the cleaner filter medium areas, creating preferential paths and causing the particles to re-deposit on the inner fibers; this increases the residual pressure drop for the next cleaning.

4.6. Particle Penetration in the Filter Media

The differences in the amount of collected mass between the filtration curves was due to differences in the packing density of the fibers. The precoated filter media, of both hydrated lime and dolomitic limestone, showed greater particle penetration, which was consistent with the longer filtration cycles obtained for these filter media compared with the PE + PTFE filter media. The absolute filters placed after the precoated filter media collected a smaller mass of particles, having three times smaller the mass of particles collected in the absolute filter after air passage through the PE 550 filter without precoating. This was also found by Schiller and Schmid (2016) [7], who performed filtration cycles using PTFE and polyimide filter media with precoating with hydrated limestone and limestone powders and observed that more powder mass was collected when the limestone dust was used. In this study, it was not possible to conclude which precoating powder had the best performance because the mass collected in the absolute filter for both precoating powders was similar. However, these results were very promising, showing that precoating increased the PE 550 filter medium filtration efficiency, obtaining less particle penetration in the filter medium innermost fibers and more mass.

5. Conclusions

Precoated filters presented higher collection efficiency for microparticles (0.523 to 4.5 μm) and filter media with encapsulation proved to be more efficient for PM3 than PE + PTFE and PE. For collect nanoparticles, polyester filter media with PTFE membrane (PE + PTFE) presented the best collection efficiency results, remaining above 90% for the entire diameter range from 3 to 300 nm due its lower porosity. Analyzing the precoating parameters, the precoat cake of hydrated lime formed at 200 Pa presented the collection efficiency almost 100% for 0.523 to 18 μm. The clogging point and the formation of the cake was reached faster when dolomitic limestone was used in the precoating, due to the lower mean aerodynamic diameter. For both hydrated lime or dolomitic limestone, the maximum pressure drop tests indicated high collection efficiency, above 90%, from a maximum pressure drop of 200 Pa. In relation to the mass mixtures varying, hydrated lime 1:0 and dolomitic limestone 1:9 were more efficient than other mixing ratios. Was also observed that the greater the proportion of hydrated lime in the precoating, the greater the collection efficiency of steelworks powder and the smaller the mass of particulate matter retained in the absolute filter. For dolomitic limestone, the higher amount caused negative changes in the collection efficiency for a range of 2 to 10 μm. However, both precoat powders presented lower penetration than filters without precoating. For filtration curves, the duration of thirty cycles in precoated filter media was higher than the duration of cycles in PE + PTFE and PE, 200–300 min and three times longer, respectively. In other words, precoating allowed for a fewer number of cleanings within a certain time period and consequently increased the filter media lifespan. In addition, the absolute filters for precoating filtrations showed three times lower retained mass than for filtration with no precoating. Therefore, precoating increased the filter media collection efficiency of the untreated filter. In the determination of particle penetration, the precoated filter had lower penetration than untreated filter media.

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