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Improved pressure drop and silica rejection of polydopamine-coated polypropylene filter media

Yesol Kang[a], Jaewon Jang[a], In Kyung Park[b], Byung-Joo Park[b], In S. Kim[a,*]

[a]*Global Desalination Research Center (GDRC), School of Earth Sciences and Environmental Engineering, Gwangju Institute of Science and Technology, 123 Cheomdangwagi-ro, Buk-gu, Gwangju, 61005, Korea, Tel. +82 62 715 2436; email: iskim@gist.ac.kr (I.S. Kim)*
[b]*SYNOPEX, 54-42, Dongtanhana 1-gil, Hwaseong-si, Gyeonggi-do, Korea*

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ABSTRACT

Cartridge filter consists of a plastic housing and simple modular melt-blown polypropylene (PP) filter media which is used to provide excellent and stable filtration performance. However, a significant differential pressure is generated in PP cartridge filters during operation of filtering system due to their hydrophobic characteristics. In this study, the surface of PP filter media was coated with polydopamine (pDA) to improve its hydrophilicity and performance. The surface characteristics of pDA-coated PP (PP-pDA) were studied by scanning electron microscopic, energy dispersive X-ray spectroscopy, Fourier transform infrared spectroscopy, and capillary flow porometer. These results showed that a pDA coating was successfully available on the surface of PP. The hydrophilicity was studied by calculation of water uptake and measurement of contact angle; water uptake of PP-pDA was improved from 37% to 298% (increased by eight times) and contact angle results showed that hydrophilicity of PP-pDA was improved (39.67°) in comparison with pristine PP (120.26°). Eventually, pure water permeability, differential pressure and silica rejections of PP-pDA filter media were improved due to its hydrophilicity. Thus, hydrophilic PP filter media coated with pDA solution could be a good choice for cartridge filters in the water treatment area.

Keywords: Filter media; Polypropylene; Polydopamine; Facile coating; Hydrophilicity

1. Introduction

Cartridge filters are currently used in water treatment, semiconductor, and pharmaceutical fields. Especially, they are used for RO pretreatment process to prevent high pressure pump and membrane damage due to large particles in seawater desalination, and also used in wastewater treatment to separate waste sewage sludge [1]. Various types of modular filters, including depth filter, pleated filter, capsule filter, hollow fiber filter, and yarn-wound cartridge filter are inserted into a plastic housing [2]. Depending on the specific application, the filter media includes materials such as polypropylene (PP), polyester (PE), nylon, and polytetrafluoroethylene (PTFE) [3].

Commonly used filter media is a non-woven fabric PP due to its non-toxicity, physical and chemical stability and low cost, which can be applied in many fields [4]. However, the hydrophobic property tends to cause severe fouling on the surface, which reduces the amount of permeate and increases the differential pressure together [5]. The concept of differential pressure is a great important factor in here, which is defined as the pressure loss between the inlet and outlet of the cartridge filter when the liquid is running. If the differential pressure is high, the performance of system is degraded and the excessive energy consumption is caused [6]. Therefore, it is important to improve the hydrophilicity of PP to prevent these problems and form a stable differential pressure. As hydrophilicity improves, the pores of

* Corresponding author.

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filter media can attract more water molecules. Therefore, the infiltration capillary force and wettability of filter media were improved [7]. Eventually, the flow rate is increased and the differential pressure decreased simultaneously. To achieve the above results, studies have been reported on surface hydrophilization by UV irradiation, plasma treatment, gamma irradiation, and chemical reaction [8–10].

Mussel-inspired polydopamine (pDA) coating method can strongly adhere to the various substrate surfaces through self-polymerization without damage on the surface of substrates when coating reaction has happened between substrate and pDA coating solution [11,12]. Also, it can improve hydrophilicity, water permeability, and rejection of substrate surface since pDA has various functional groups such as catechol and amine, which eventually improve surface hydrophilicity and reduce the differential pressure [13].

In this work, we coated a pDA layer on the surface of commercial polypropylene filter media to improve its hydrophilicity. The morphologies and hydrophilicity of polypropylene with/without pDA coating layer and its effect on differential pressure, outflow rate, and rejection of water against micro-sized silica particles were also be studied. The results of current work give important suggestions for the improvement of low differential pressure and highly selective filter media surface coating.

2. Materials and methods

2.1. Materials

PP filter media was supplied by Synopex (Dongtan, Korea). Dopamine hydrochloride (Sigma-Aldrich, USA) and 1.5 M Tris (hydroxymethyl) aminomethane buffer solution (Tris-HCl buffer solution, Biosesang, Seongnam, Korea) were used for pDA coating process. Three different sizes of silica spherical powder were obtained (0.8, 10, and 20 μm) from US Research Nanomaterials Inc., USA.

2.2. pDA coating on PP filter media

The pDA coating method is described in Fig. 1. It was performed as provided in our group's previously published document [14]. Briefly, 100 g/L of dopamine stock solution was prepared by dissolving dopamine hydrochloride powder in DI water. Next, 2 mL of stock solution was added into 100 mL of Tris-HCl buffer solution, and the mixed solution was stirred for a short time. The ethanol pre-wetted PP filter media was fully soaked into the dopamine solution in a plastic container for 2 h, respectively. The plastic container was placed on a shaking plate to supply oxygen during self-polymerization of dopamine monomers. After finishing all the experiments, the sample was fully cleaned with DI water and dried at room temperature.

2.3. Characterization of filter media

The top surface morphology and elemental distribution of PP and pDA coated PP (PP-pDA) filter media were investigated using scanning electron microscopy (SEM, S-4700, Hitachi, Japan) and energy dispersive X-ray spectroscopy (EDX, 7200-H, Horiba, USA). The chemical structure and functional groups were detected by Fourier transform infrared spectroscopy (FTIR, Spectrum 400, PerkinElmer, USA). Capillary flow porometer (CFP-1500AEL, PMI, USA) measured mean pore diameter (MPD), and bubble point diameter (BPD). The water uptakes was calculated by the difference between wet weight ($W_{wet,W}$) and dry weight ($W_{dry,W}$) of each sample. Before measuring $W_{wet,W}$ of samples, the filter media were soaked into DI water for 24 h under ambient condition, and we weighed the samples after wiping out excess water on the surface with tissue paper. The filter media were dried in an oven at 60°C for 24 h and weighed to measure the $W_{dry,W}$. The water uptakes were calculated using the following Eq. (1) [15]:

$$\text{Water uptake}\,(\%) = \frac{W_{wet,W} - W_{dry,W}}{W_{dry,W}} \times 100 \tag{1}$$

The porosity (ε) of filter media was measured by a gravimetric method with ethanol [16]. A measurement method was similar to the water uptake measurement process. The only difference was that the applied solution was changed into ethanol. After weight measurement, porosity was calculated using Eq. (2):

$$\varepsilon(\%) = \frac{\dfrac{W_{wet,E} - W_{dry,E}}{\rho_{ethanol}}}{\dfrac{W_{wet,E} - W_{dry,E}}{\rho_{ethanol}} + \dfrac{W_{dry,E}}{\rho_{polymer}}} \times 100 \tag{2}$$

where $W_{wet,E}$ and $W_{dry,E}$ are the weight of wet and dry filter media, $\rho_{ethanol}$ and $\rho_{polymer}$ are the densities of ethanol (0.789 g/cm^3) and polymer (0.946 g/cm^3), respectively.

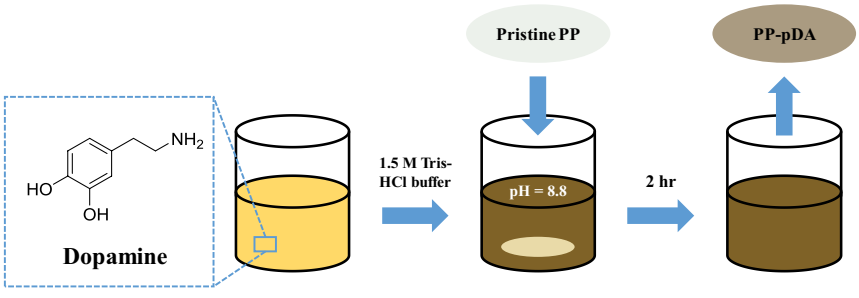

Fig. 1. Schematic description of pDA coating process of PP filter media.

The contact angles were determined using contact angle analyzer (Phoenix 300, Surface Electro Optics Co., USA) according to sessile drop technique. Each sample was measured with five different points and they were averaged to minimize the experimental error.

2.4. Permeation, differential pressure, and silica rejection of filter media

Permeability, differential pressure, and silica rejection were studied using a dead-end filtration test system with an effective filter area of 7.07 cm^2, and 10 sheets of prepared filter media were stacked to affect a depth-filtration. Fig. 2 shows the schematic diagram of the filtration system. The pure water permeability (PWP) and differential pressure (ΔP) of filter media were measured by changing the operating flow rate at 100, 200, 300, 400, and 500 mL/min. Those were calculated using Eqs. (3) and (4), respectively:

$$\mathrm{PWP} = \frac{V}{A \cdot \Delta t \cdot \Delta P} \tag{3}$$

$$\Delta P = P_{\mathrm{in}} - P_{\mathrm{out}} \tag{4}$$

where V is the amount of permeate volume (L), A is the membrane effective area (m^2), Δt is operating time (h), P_{in} is upstream pressure (bar), and P_{out} is downstream pressure (bar).

The silica rejection test was performed with different sizes of silica (0.8, 10, and 20 μm) for 20 min and permeate samples were collected every 5 min. The concentration of silica feed solution was fixed in 0.25 g/L. Optimum operating flowrate was changed depending on the size of silica particle. 100 mL/min of flow rate was selected when feeding 0.8 μm sized silica dissolved solution, and then the flow rate was changed into 200 mL/min when rejecting 10 and 20 μm sized silica. The turbidity removal efficiency (R_T) was defined as Eq. (5):

$$R_T(\%) = \left(1 - \frac{C_p}{C_f}\right) \times 100 \tag{5}$$

where C_p and C_f are the turbidity of silica particles in the permeate and feed solution, which were determined by a turbidity meter (2100N, Hach, USA).

To anticipate the trends of performance after 60 min, 0.8 μm size dispersed silica feed solution was filtrated through filter media for 1 h. Simultaneously, differential pressure and permeate samples were calculated and collected at 5, 10, 15, 20, 40, 50, and 60 min. Also, silica rejection of every sample was calculated using Eq. (5).

3. Results and discussion

3.1. Morphology and hydrophilicity of filter media

When pDA was formed from dopamine monomers, the colorless and transparent dopamine solution was turned dark brown by oxidation with oxygen. Therefore, as shown in Fig. 3a, the surface of PP-pDA filter media was dyed light

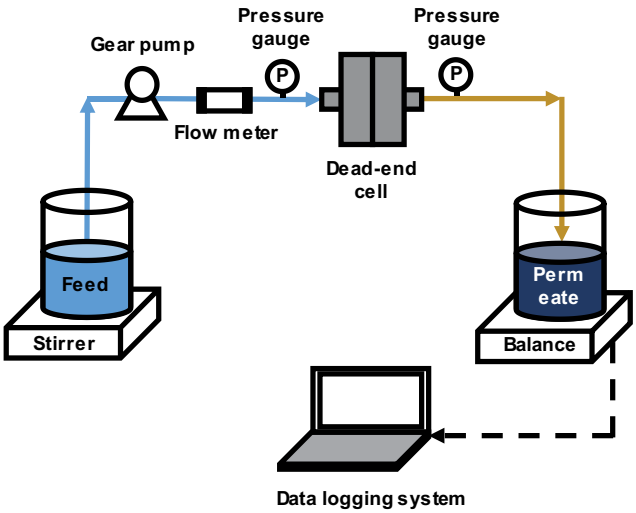

Fig. 2. Schematic diagram of the filtration system for filter media performance test.

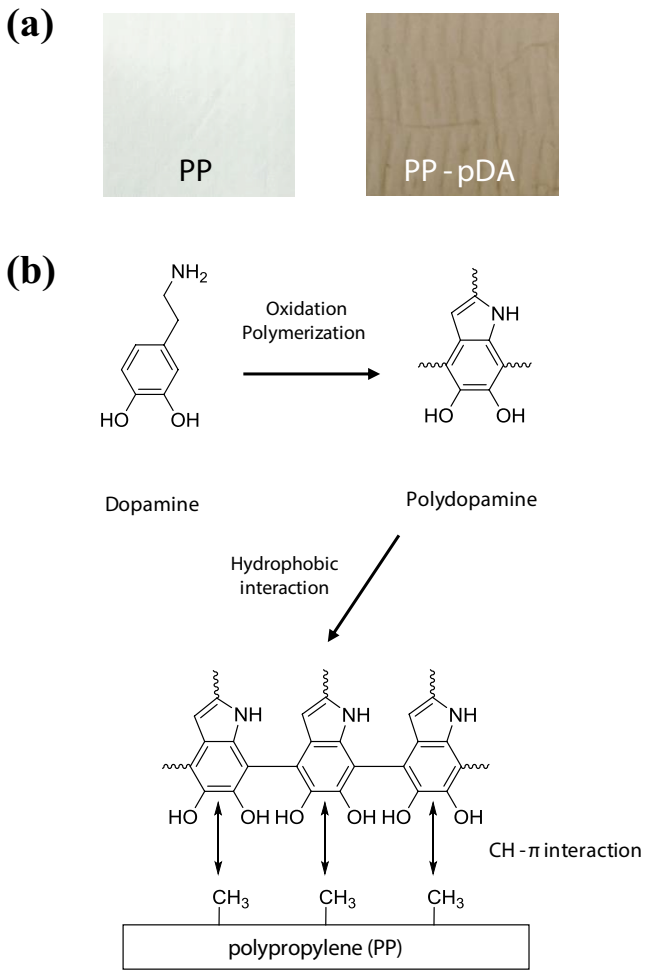

Fig. 3. (a) Digital images of filter media surfaces and (b) reaction scheme of oxidation polymerization and hydrophobic interaction between pDA and PP filter media.

brown after coating the pDA on the PP. Fig. 3b explains the interaction between pDA layer and PP filter media. pDA layer covered a hydrophobic PP surface by hydrophobic interactions such as CH–π interaction which denoted that the alkanes (–CH) of PP were in alignment with p-orbital on the catechol groups of pDA and they were geometrically reacted each other [17,18].

Fig. 4 presents the SEM images of pristine PP and pDA-coated PP filter media. It was performed to check whether pore-blocking and fiber deformation were occurred or not due to the pDA coating. As can be seen in Figs. 4a and b, the fibers of pristine PP filter media have smooth morphology and the pores were also available very well without any pore blocking phenomenon. Figs. 4c and d exhibit the shape of PP-pDA filter media. After pDA coating, its morphology existed without any severe changes, for example, pore blockage did not happen and the fibers also did not shrink. It is because the pDA coating exists very thinly on the fiber surface; therefore, the morphology of the PP-pDA filter media was not affected.

The weight and atomic percentages of elements were studied by EDX (Table 1). It was observed that the carbon percentage of pristine PP filter media was higher than 90%. After coating with pDA, the carbon percentage of PP-pDA was decreased to 85.5%, but the percentage of nitrogen element content was increased to 5.04%. The reason for nitrogen percentage growth is the existence of the amine groups in pDA layer, and it means that pDA coating was successfully formed on the PP surface.

The FTIR spectra were studied to have confidence that pDA coating layer was successfully formed on the surface of PP. According to Fig. 5a, the spectra on the peak 2,951 and 2,918 cm^{-1} describe CH stretch bond, also other peaks on 1,456 and 1,376 cm^{-1} indicate the CH_2 deformation and symmetric CH_3 deformation of PP filter media, respectively [19]. Moreover, the new peaks at around 1,671; 1,542; and 1,052 cm^{-1} have appeared in PP-pDA filter media, which were amide I band, amide II band, and C–O stretching vibrations [20,21]. These peaks were derived from C–N stretching, –NH bending, and catechol groups, demonstrating that the pDA coating layer was successfully formed on the PP filter media surface and potentially improved the hydrophilicity of filter media. This consequence would be confirmed by contact angle measurement.

The surface hydrophilicity characteristic plays a key factor in reducing the pressure differences, which can extend the lifespan of the cartridge filter. The contact angle and porosity of PP and PP-pDA filter media are presented in Fig. 5b. PP had a water contact angle of 120.26°, indicating that it had hydrophobic property. In contrast, the contact angle of PP-pDA had greatly decreased to 39.67° by pDA hydrophilic coating, which suggests that the pDA coating with hydrophilic groups (amide and catechol groups) tend to improve the hydrophilicity of PP filter media. In the case of porosity, the value of PP and PP-pDA filter media did not change greatly due to pDA coating layer did not block the pores as shown in SEM images (Fig. 4).

Table 2 presents MPD, BPD (i.e., the maximum pore size), and water uptake values of filter media. Both MPD and BPD of PP-pDA were similar to those of pristine PP. Through these results, it can be demonstrated that the existence of coating layer did not block the filter pores. The water uptake indicated the water-filled in the pores of the filter media; therefore, the water adsorption amount of filter media was studied by measuring water uptake. In comparison with the water uptakes of PP and PP-pDA, PP-pDA showed eight times higher than that of the pristine PP. It is because of the

Table 1
EDX results of the weight percentage of PP and PP-pDA

Sample	Percentage	Element content		
		Carbon	Oxygen	Nitrogen
PP	Weight (%)	90.15	9.85	–
PP-pDA	Weight (%)	85.50	9.46	5.04

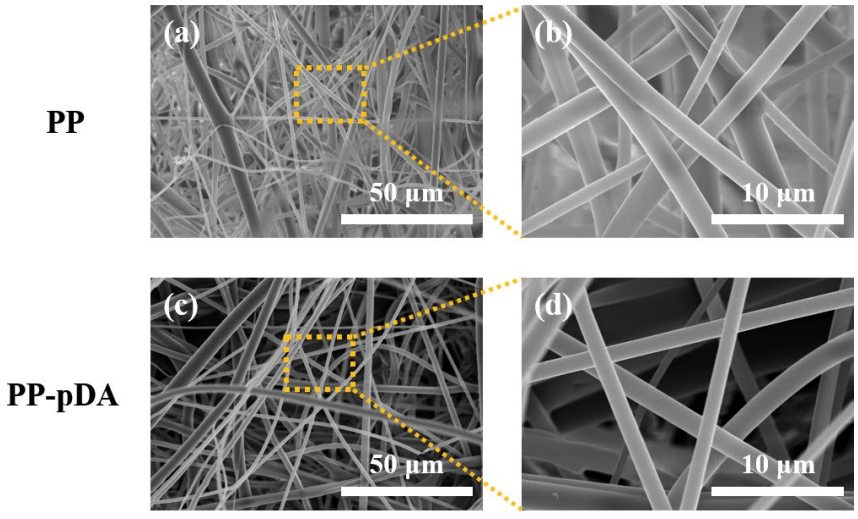

Fig. 4. SEM images of; (a, c) 1,000× magnification and (b, d) 5,000× magnification of PP and PP-pDA filter media, respectively.

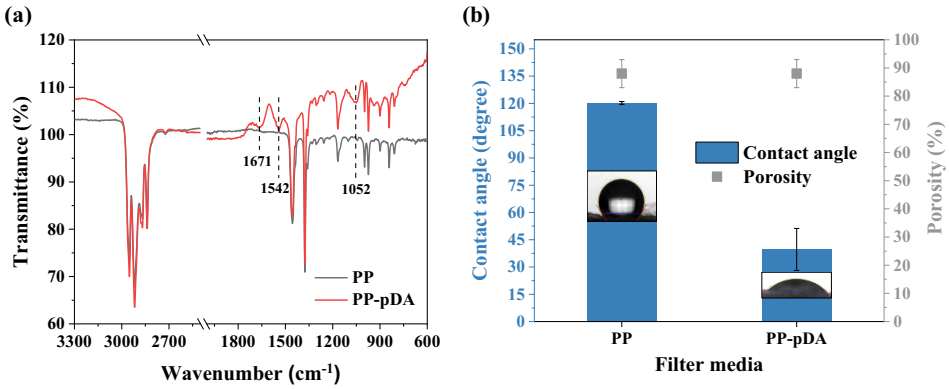

Fig. 5. (a) FTIR spectra and (b) water contact angle and porosity of PP and PP-pDA filter media.

Table 2
Comparison of MPD, BPD, and water uptake in PP and PP-pDA

	MPD* (μm)	BPD** (μm)	Water uptake (%)
PP	10.57	13.66	37
PP-pDA	11.18	15.10	298

*MPD: mean pore diameter.
**BPD: bubble point diameter.

combined effect of improved hydrophilicity and high porosity of PP filter media.

3.2. *Pure water permeability, differential pressure, and rejection of stacked filter media*

Fig. 6 presents the PWP and Δ*P* results obtained from the dead-end filtration of the 10 layers stacked filter media. The flow rate increased from 100 to 500 mL/min at 100 mL/min intervals, and the average values of PWP and Δ*P* of filter media samples were compared in Fig. 6a. Those values were improved gradually with increasing the inflow rate. In the case of PWP, PP-pDA was overwhelmingly higher than PP (increased by 1.58–2.06 times); furthermore, the pressure differences of PP-pDA were 0.08–0.11 bar less than that of PP filter media. The permeability and differential pressure of the filter media are related to its hydrophilicity and water uptake ability. Filter media with high hydrophilicity and water uptake have higher water permeance, whereas filter media with hydrophobicity and low water uptake have lower water permeance. With enhanced hydrophilicity and water uptake by pDA coating, the PP-pDA filter media exhibited much greater permeability than the PP. The differential pressures of PP-pDA were 0.1 bar less than PP since hydrophilic filter fibers allowed water molecules to pass quickly and remain around the filter fibers easily.

Fig. 6b shows the PWP and Δ*P* of filter media samples evaluated by the stepping experiment at different inflow rates. The tests were performed for 300 min and data were collected every 5 min with changing the inflow rates every hour. The trend of PWP and differential pressures were increased together with improving inflow rates. Particularly in Δ*P* results, PP trend shows that the values were increased with longer operation time. However, PP-pDA exhibited different trends that the values were decreased with longer operation time and then became stable. These results indicate that the enhancement of hydrophilicity can significantly change the PWP and differential pressure together.

Fig. 7 indicates the silica rejection percentage and the resulting differential pressure when supplying 0.8, 10, and 20 μm sized silica particles, respectively. The differential pressure was recorded and permeate samples were collected every 5 min. After measuring the turbidity of collected samples, silica rejection of PP and PP-pDA was calculated and compared a difference. All experimental results showed that the differential pressure of PP-pDA exhibited lower than that of PP filter media, and the rate of increase has been increased rapidly when the silica particle size decreased from 20 to 0.8 μm. Especially, when rejecting 0.8 μm sized silica, the differential pressure of PP-pDA constantly exhibited 0 bar; however, in the case of PP, it was increased from 0.025 to 0.25 bar (Fig. 7a). The results were related to a hydrophilic pDA coating layer of PP-pDA, which can directly block the contact between hydrophobic PP filter media and silica particles (hydrophobic). Therefore, the amount of silica particle sorption and rate of passage were decreased, resulting in low differential pressure and high silica rejection [22]. However, when using 10 or 20 μm sized silica dispersed feed solution, the rejection of both filter media samples was higher than 95%, since the mean pore sizes (10–11 μm) of filter media samples were sufficient to reject the silica particles (Figs. 7b and c). Therefore, it was possible to reject them highly due to the sieving effect of PP filter media.

To predict the trends of differential pressure and silica rejection of PP and PP-pDA filter media, the experiment was further performed for 60 min using 0.8 μm sized silica particles (Fig. 8). The gap of differential pressure after 40 min between PP and PP-pDA was getting higher than that of results until 20 min, and when the experiment performed for 60 min, pressure drops were reached to 1.3 and 2.5 bar for PP-pDA and PP, because cake layers were formed. In the case of silica rejection, it was increased over time since silica particles formed a thick layer on the surface of the filter media and no longer allowed the silica particles to pass through filter media properly. Also, the silica rejection arrived at more than 95% after 34 min for PP-pDA, but it takes about 53 min for PP filter media. Throughout these results, the PP-pDA filter

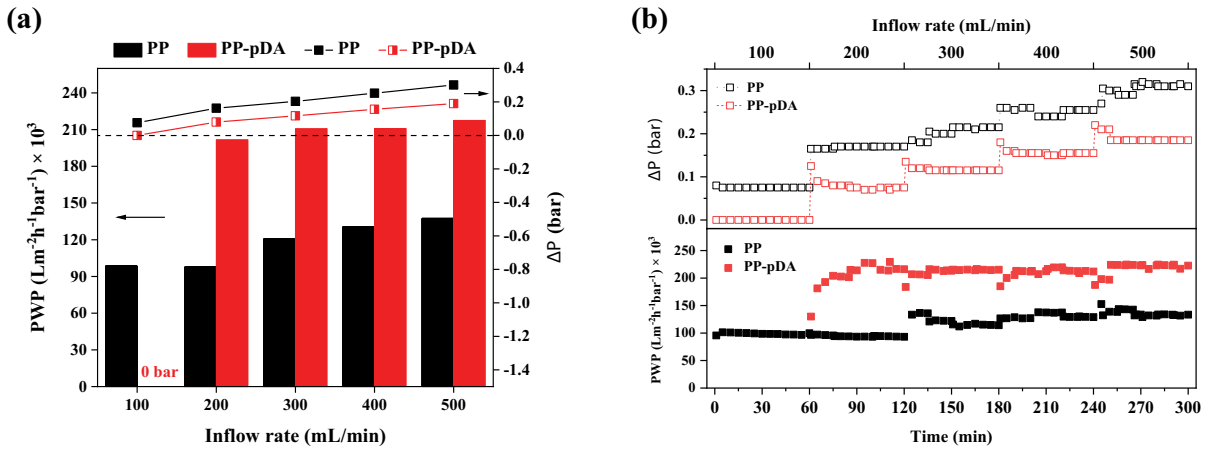

Fig. 6. PWP and Δ*P* (pressure differences) result of filter media (a) depending on their inflow rate changes and (b) using a stepping method by changing the inflow conditions every hour for 5 h.

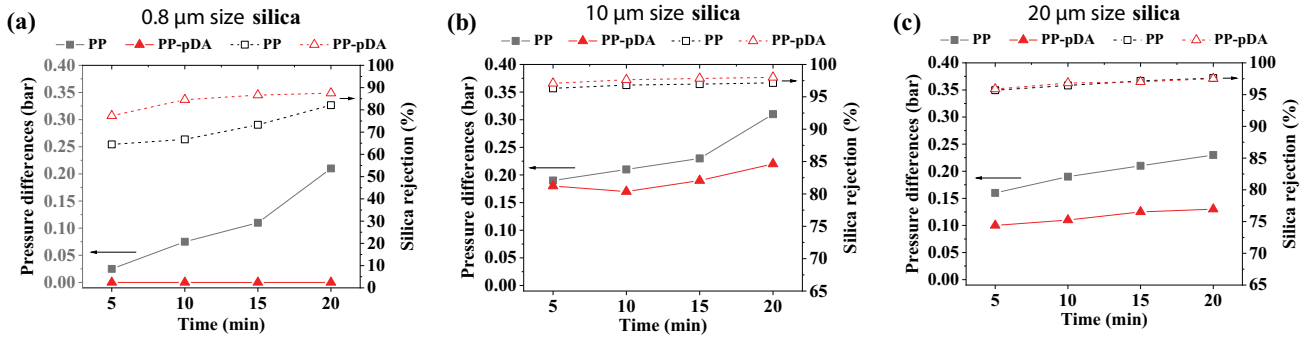

Fig. 7. Pressure differences and silica rejection comparison of filter media depending on the silica particle size: (a) 0.8, (b) 10, and (c) 20 μm.

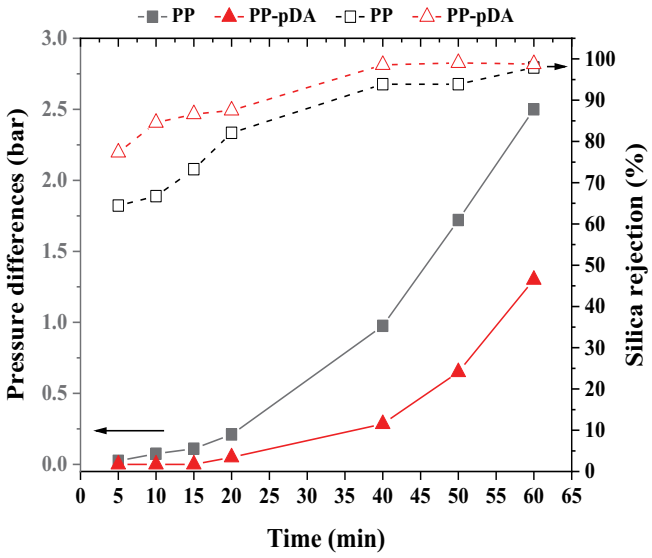

Fig. 8. Pressure differences and silica rejection trend of PP and PP-pDA filter media depending on time using 0.8 μm size of silica.

media with hydrophilicity showed lower differential pressure and higher silica rejection than pristine PP.

4. Conclusions

The coating of pDA layer was successfully formed on the surface of PP filter media. SEM images showed that no pore blocking and fiber deformation. Also, the results of EDX and FTIR evidenced that pDA was available on the surface. Thus, the shapes of pristine PP and PP-pDA filter media were very similar to each other and the pDA coating method did not cause any severe defect to PP filter media during polymerization. Moreover, PP-pDA filter media had highly hydrophilic characteristics, which can improve water permeability and decrease the pressure differences. Also, in silica rejection experiment, rejection was increased and at the same time silica rejection during silica rejection test and decrease the pressure differences. PP-pDA filter media exhibited low-pressure differences, through those result hydrophilic filter media can be used much longer time with improved silica rejection. In conclusion, PP filter media modified with hydrophilic materials could use longer than a pristine one, eventually reducing the replacement cycle.

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