Fiber filter built with polypropylene fibers applied to water clarification

Alice K. M. Morita and Marco A. P. Reali

ABSTRACT

Flexible fiber filters are recently developed modular filtration units which have been applied to wastewater and water treatments, satisfactorily removing solids even when operated at high application rates. In this paper, polypropylene fibers, in lieu of the commonly used polyamide fibers, were tested for constructing filtration modules containing parallel fibers. The studied fibers were analyzed by means of scanning electronic microscopy and through solubility assays in hydrochloric acid and sodium hydroxide, aiming to evaluate the risks of using them as filtering media. Three polypropylene filters with different lengths (25, 60, and 100 cm) were constructed and fed with the same raw synthetic water. In-line coagulation was applied by addition of aluminum sulfate (22.5 mg·L^{-1}) and filtration rates from 20 to 80 m·h^{-1} were evaluated. Filtrates with less than 0.5 NTU could be produced by both 60 and 100 cm filters, operating at 80 m·h^{-1}. High filtration rates, as well as significant backwashing water and air flows, could be applied to flexible fiber filters made of polypropylene, which shows their promising applications.

Key words | deep bed fiber filtration, flexible fiber filter, polypropylene, water clarification

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INTRODUCTION

The adaptation or substitution of processes normally used in conventional water treatment can be adopted in order to simplify, optimize or reduce costs without decreasing the effluent's quality. Flexible fiber filters (3Fs) are innovative and recently developed technologies that can be used in water treatment, in some situations substituting the conventional sand filtration units and producing satisfactory filtrates at considerably high application rates (Lee *et al.* 2006, 2008a; Guerra *et al.* 2014; Niu *et al.* 2015).

These filters consist of filtration modules that use, instead of sand, bundles of fine polyamide fibers with an average diameter of around 30 μm, which are packed parallel to the water flow. Fibers are attached on the bottom of the filter bed and are left loose on its top. Upward flow is employed, and deep filtration occurs through all the filter bed. This combines large specific surface area and large porosity, which permits high removal efficiencies and low pressure drops to be achieved, despite the high filtration velocities applied and the high effluent turbidity. This technology has been used in South Korea for several years, especially applied to industrial effluent's tertiary treatment, after the conventional activated sludge treatment. For these applications, filtrates with values of turbidity and chemical oxygen demand (COD) below 2 NTU and 10 ppm, respectively, were obtained when operated at rates as high as 150 m·h^{-1} (Ben Aim *et al.* 2004).

Even though the 3F use for wastewater treatment does not require the application of coagulants, their adoption is essential for the clarification of drinking water. Therefore, this efficient technology can be used for water treatment as a direct filtration unit (Lee *et al.* 2006, 2008a), with the advantage of being possibly applied to the clarification of water with higher levels of turbidity and/or with higher application rates, when compared with the conventional

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sand filters. This can be explained by the large porosity and the low pressure drop observed in 3Fs, permitting the retention of larger amounts of particles (Guerra *et al.* 2014; Niu *et al.* 2015, 2016).

Aiming to assess the application of 3Fs for the clarification of drinking water, Lee *et al.* (2006) studied filters with a diameter of 114 mm, length of 1,500 mm, and porosity of 93%, using polyamide fibers with diameters of 30 μm. The applied raw water was obtained from the Nakdong River without any pre-treatment, which presented turbidity values ranging from 8 to 11.5 NTU. After evaluating rates from 80 to 150 $m \cdot h^{-1}$, they concluded that the best condition was obtained for the rate of 120 $m \cdot h^{-1}$, using 1 $mg \cdot L^{-1}$ of PAC (polyaluminum chloride) as coagulant. This condition showed that flexible fibers are efficient at rates higher than the conventional sand filters, and using less coagulant than those, which leads to lower sludge production. In a similar study, Lee *et al.* (2008a) compared the filtrates from flexible filters with the ones from sand filters and concluded that the first presented higher quality.

3Fs have already been applied to several wastewater treatment plants in Korea (Ben Aim *et al.* 2004) and evaluated for the reuse of wastewater (Denieul *et al.* 2011; Mauchauffee *et al.* 2012), the clarification of surface water (Lee *et al.* 2006, 2007, 2008a; Guerra *et al.* 2014; Niu *et al.* 2015, 2016), seawater particle removal as pre-treatment for reverse osmosis (Jeanmaire *et al.* 2007; Lee *et al.* 2009, 2010; Kim *et al.* 2013), stormwater treatment (Johir *et al.* 2009) and algae removal (Cha *et al.* 2009).

Even though comprehensive studies have already been conducted, it is still necessary to continue evaluating this promising technology, by investigating different conditions and configurations, as well as by assessing the use of other fibers as filter media and other types of coagulants.

Normally built with polyamide fibers, the flexible fiber filter configuration could possibly work with different kinds of long fibers, which could reduce its cost and make it more appropriate to different contexts. Polypropylene is a cheaper synthetic fiber known for being resistant to acid and basic media (Moore 1996; Ebnesajjad 2013). These characteristics may contribute to its use as filter media.

Gao *et al.* (2012) used polypropylene fibers in a filter with a different configuration (fiber-ball filter), obtaining interesting results when using high turbidity raw water and filtration rates as high as 50 $m \cdot h^{-1}$. Only one study was found in the literature (Guerra *et al.* 2014) which adopted polypropylene fibers as filter media in flexible fiber filters. This study evaluated the performance of short filters (40 cm long) in the clarification of raw water with high turbidity but did not aim at producing water with turbidity as low as 0.5 NTU (suitable for drinking purposes). Additionally, all the studies before mentioned adopting PAC as coagulant, which is different from the coagulant used in this research.

This paper shows the results of studies using polypropylene fibers as filter media in flexible fiber filters, aiming to evaluate different filter lengths and filtration rates, as well as the adoption of aluminum sulfate as coagulant ($Al_2(SO_4)_3 \cdot 14H_2O$). This way, it can contribute to the development and better understanding of this type of technology, enabling the adaptation of its configuration to include the use of different fibers and distinct coagulants, which are sometimes cheaper and more available in different countries.

METHOD

The experimental work was divided into four phases. In the first phase, polypropylene fibers – obtained from ropes sold for agricultural purposes (see Figure 1 of the Supplementary Material, available with the online version of this paper) – were characterized in order to evaluate their use as filter media. In the second part, laboratory-scale batch coagulation equipment (Jar test) was used to perform a preliminary investigation aiming to determine the best coagulation condition for the studied synthetic water. In the third part, filtration tests were conducted with three different filter lengths (25, 60, and 100 cm) and three application rates (20, 40, and 80 $m \cdot h^{-1}$), using, for all assays, the same raw synthetic water and the coagulant dosage found in the previous phase. Finally, in the fourth part of this study, backwashing studies were conducted, by application of air and water in sequence. A detailed description of each phase is presented below.

Characteristics of synthetic raw water

The same synthetic raw water was used for the second, third and fourth phases of this research. It was produced by the addition of 1.0 $mg \cdot L^{-1}$ of humic acid (Aldrich 1675-2), 8.5 $mg{\cdot}L^{-1}$ of kaolin (Fluka 60609), and 10 $mg{\cdot}L^{-1}$ of sodium carbonate (for pH adjustment) to deep well water. The values of pH, turbidity, and apparent color (CU) of the synthetic water were 7.37 ± 0.22, 8.19 ± 0.85 NTU, and 14.47 ± 5.25 CU, respectively, and the concentration of suspended solids was 7.98 ± 0.74 $mg{\cdot}L^{-1}$. This synthetic water was used to simulate conditions similar to the ones found in the literature (Lee *et al.* 2006, 2008a, 2008b), enabling a better comparison of the results. Other parameters of the study water are presented in Table 1 of the Supplementary Material (available online).

First phase of work

For solubility assays, two polypropylene fiber samples of 50 g each were previously washed with distilled water and dried in a drying oven at 110 ± 5 °C for 3 hours. From the first sample, 30 g (a_1) were weighed and immersed in hydrochloric solution (1:1) for 30 minutes, with intermittent mixing. From the second sample, 30 g (b_1) were weighed and immersed in sodium hydroxide solution (1%) for 24 hours, with intermittent mixing. After the immersion periods, the samples were washed by decantation with distilled water until pH 7.0 was achieved and dried at 110 ± 5 °C for 3 hours. The fibers were weighed again (a_2 for polypropylene mass after acidic immersion and b_2 for polypropylene mass after basic immersion) and the solubility in hydrochloric acid and sodium hydroxide could be obtained by:

$$\%\text{Acid Solubility} = 100\cdot\ (a_1 - a_2)/a_1$$
$$\%\text{Base Solubility} = 100\cdot\ (b_1 - b_2)/b_1$$

For scanning electronic microscopy (SEM) analysis, fiber samples were dried at 110 °C ± 5 °C for 24 hours and prepared on a metallic support with gold coating. The microscopies were conducted for four different fiber samples: (a) without any treatment or use as filtering material, (b) after 3 months of operation in fiber filters, (c) after solubility assays in hydrochloric acid, and (d) after solubility assays in sodium hydroxide.

Second phase of work

In this phase, batch coagulation equipment (Jar test) containing six 2 L jars was used. Ten series of coagulation tests were conducted. In each series, the coagulant dosage was kept constant and pH was varied among the jars through the addition of sodium carbonate or sulfuric acid. Dosages from 5 $mg{\cdot}L^{-1}$ to 50 $mg{\cdot}L^{-1}$ of aluminum sulfate ($Al_2(SO_4)_3{\cdot}14H_2O$) and pH from 5.5 to 7.0 were evaluated. The following parameters were fixed during the Jar test investigations: water temperature of 24 ± 1 °C, average velocity gradient (G) of 900 s^{-1}, and detention time of 20 seconds during the rapid mixing step.

After the rapid mixing step, samples from each jar were collected and filtered through Whatman 40 paper filters. The filtrates' turbidity, color, and pH were evaluated, and a coagulation diagram was built for the selection of the best coagulation condition.

Third phase of work

The third phase of experiments was conducted by using filters with three different lengths (25, 60, and 100 cm) fed with the synthetic water previously described. The filters were built with pipes whose internal diameters were 28 mm. The filter media was packed parallel to the vertical axis and the fibers were fixed to a stainless steel net located on the bottom of the filter. The porosity obtained for this layout was 93%. Four equally spaced points of pressure measurement were installed in each filter, and the pressure drop was observed with a piezometer. Upflow filtration was conducted, and the feed water flowed by gravity from a constant level box installed at approximately 3 metres high, which permitted each filter to have an available hydraulic load of around 2 mH_2O (see Figure 1).

Aluminum sulfate ($Al_2(SO_4)_3{\cdot}14H_2O$) solution was applied by using a static tubular mixer installed in the feed pipe to promote the coagulation of the raw water. The coagulant dosage was kept constant during this step (for all filters and conditions), and its value was equal to the best one found during the previous phase (Jar test). Three different filtration rates (20, 40, and 80 $m{\cdot}h^{-1}$) were evaluated, and, during each condition, the filtration process was stopped when filtrate turbidity achieved 1.0 NTU or when the pressure drop was higher than 1.8 mH_2O. Filtrate and raw water samples were collected every 15 minutes, and the following parameters were evaluated: pH, turbidity, true and apparent color, alkalinity, and suspended solids.

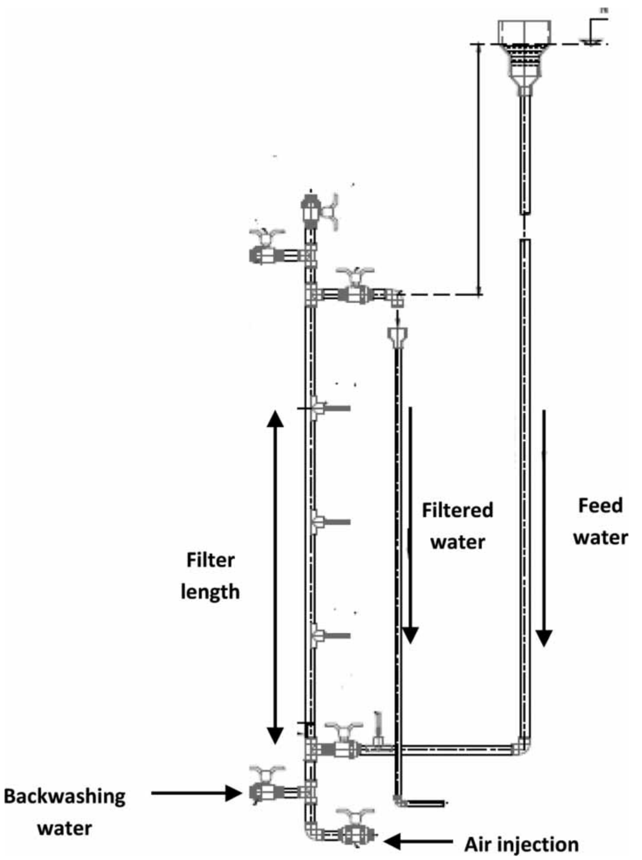

Figure 1 | Scheme of the fiber filter used in this study.

The methods and equipment used for measuring these parameters are shown in Table 2 of the Supplementary material (available online). Pressure drop and water flow were also monitored every 15 minutes.

After turbidity or pressure drop limit was achieved, backwashing was executed in order to clean the filter media and restart the filtration runs; each condition was conducted in duplicate. At this stage, backwashing was not optimized, and its efficiency was guaranteed by maintaining the pressure drop after cleaning equal to the one before the filter run.

Fourth phase of work

The backwashing process was evaluated only for the filters with better performances, by varying the number of stages and time of air application. The conditions analyzed were: (i) application of water only, for 60 seconds (Mode 1); (ii) use of compressed air for 15 seconds followed by application of water for 30 seconds (Mode 2); (iii) use of compressed air and water in three subsequent series, each of them consisting of the application of air for 5 seconds followed by the application of water for 10 seconds (Mode 3); (iv) use of compressed air and water in three subsequent series, each of them consisting of the application of air for 10 seconds followed by the application of water for 10 seconds (Mode 4); (v) use of compressed air and water in five subsequent series, each of them consisting of the application of air for 3 seconds followed by the application of water for 6 seconds (Mode 5); and (vi) use of compressed air and water in five subsequent series, each of them consisting of the application of air for 6 seconds followed by the application of water for 6 seconds (Mode 6). The applied air flow rate was kept at about 160 $m^3 \cdot m^{-2} \cdot h^{-1}$, and the applied backwashing water flow rate, in this stage, was fixed at approximately 1,040 $m^3 \cdot m^{-2} \cdot h^{-1}$. In a second stage, the water flow was reduced to 300 $m^3 \cdot m^{-2} \cdot h^{-1}$ and the backwashing performance for the best condition found in the first phase (number of stages and time of air and water application) was analyzed.

The backwashing performance was assessed considering (a) the recovery of pressure drop and (b) the mass balance between the solids retained in the filtration process and the solids observed in the backwashing water.

RESULTS AND DISCUSSION

Results of the first phase of experimental work

Hydrochloric acid and sodium hydroxide solubilities for polypropylene fibers were, respectively, 4.99% and 0.21%. There is still no solubility standard for filters with polypropylene fiber beds. Thus, only as an example of standardization for other filtering materials, it is worth mentioning that the Brazilian standard NBR 14234/1998 recommends that for anthracite coal used in water treatment these values should not exceed 5% and 2%, respectively. From this standard, polypropylene fibers seem to be adequate as filtering media; nonetheless, future studies will be needed to establish which solubility values are permissible for polypropylene beds. Therefore, it is important to emphasize that before polypropylene fibers are used as filter media, studies focusing on the chemicals they possibly release to water are necessary, in order not to pose risks to public health.

Through SEM analysis (see Figure 2), it could be observed that polypropylene fibers are considerably uniform, with diameters of about 34 μm, similar to polyamide fibers. These small diameters may be associated with higher filtration surfaces (Lee *et al.* 2006). Images before and after solubility assays were analogous, showing no degradation evidence. On the other hand, residues could be observed on the surface of fibers used as filtering media for 3 months. This showed the effectiveness of the filtration process, with attachment of solids on the fibers' surface.

Results of the second phase of experimental work

Diagrams for 80%, 90%, and 95% of turbidity and color removal were constructed for different values of pH and coagulant dosage applied during the jar test. The highest removal efficiencies were obtained for dosages from 20 to 25 mg·L^{-1} and pH from 6.5 to 7.0. Consequently, we chose as best condition for the third phase of the experiments dosages of 22.5 mg·L^{-1} of aluminum sulfate ($Al_2(SO_4)_3.14H_2O$), pH of 6.5 ± 0.2 and temperature of 25 ± 1 °C.

Results of the third phase of experimental work

Satisfactory filtrates were produced by all filters at 20 m·h^{-1}, even the one of 25 cm, and the filter run times were proportionally longer as the filter length increased (see Figure 3). This way, the filter run lasted about 100 minutes for the 25 cm filter, whereas it lasted about 500 minutes for the 100 cm filter. Associated with these filter runs, the 100 cm, 60 cm, and 25 cm filters produced, respectively, 145 L, 82 L, and 23 L of clarified water. This represented, for the 100 cm filter, a production of clarified water 2,400 times higher than the filter volume. For all the studied filters, deep filtration was observed, with the use of all the filter length, as can be observed in Figure 2 of the Supplementary Material (available with the online version of this paper).

On the other hand, for the filtration rate of 40 m·h^{-1}, the shorter filter (25 cm long) could not produce filtrate with satisfactory quality, and the filtration process stopped after about 100 minutes for the filter of 60 cm (due to the turbidity limit) and after about 150 minutes for the filter of 100 cm (owing to the head-loss limit). Figure 3 of the Supplementary Material (available online) shows the turbidity evolution for the filtration rate of 40 m·h^{-1}. For this rate, the 100 cm and 60 cm filters could produce, respectively, 87 L and 62 L of clarified water, which represented about 1,500 times the filter volumes, for both cases. If only the volume of clarified water is to be evaluated, it is clear that the longer filter is more efficient; however, if head loss is to be considered, the 60 cm filter shows better performance.

For application rates of 80 m·h^{-1}, the filter with 25 cm could not work within the established turbidity limit. The filter run lasted about 40 minutes for the 60-cm-long filter, after which the turbidity limit (1.0 NTU) was achieved and all parts of the filter were working (see Figure 4 of the Supplementary Material, available online). This filter could also produce filtrate with less than 0.5 NTU for about 30 minutes, which shows the possibility of its use at high rates even for restrictive standards. For this condition, the

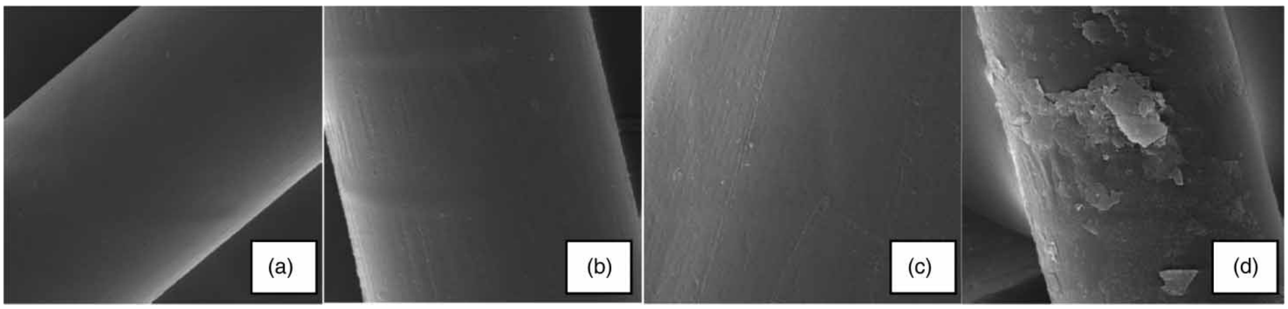

Figure 2 | Images from scanning electron microscopy with magnification of 2,000×: (a) without any treatment or use as filter media, (b) after solubility assay in hydrochloric acid, (c) after solubility assay in sodium hydroxide, (d) after use as filtering material for 3 months.

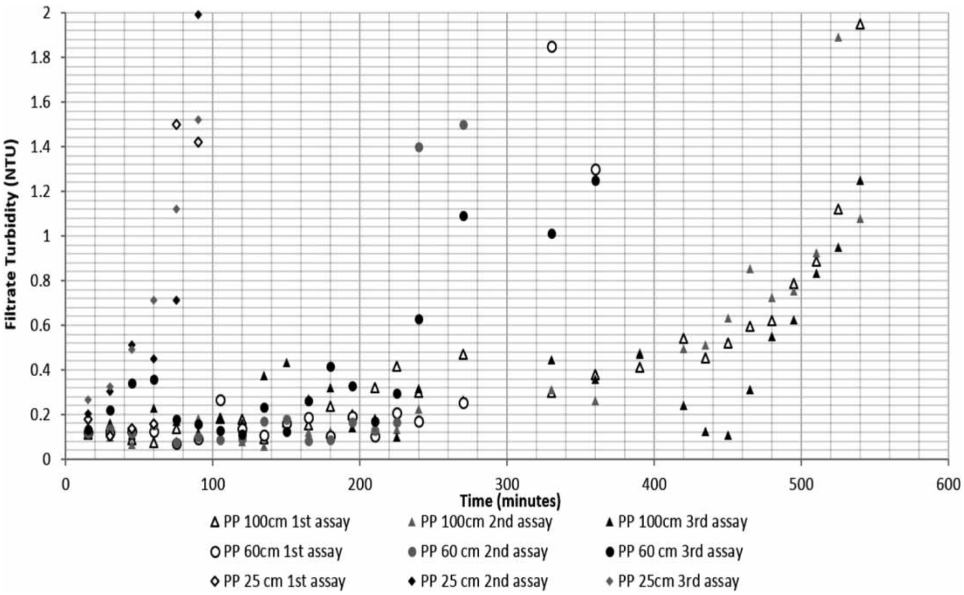

Figure 3 | Filtrate turbidity evolution for filters studied and for the application rate of 20 m/h.

60 cm filter could produce 56 L of clarified water, which represents 1,500 times the filter volume.

Although the filter of 100 cm achieved the head-loss limit (1.8 mH_2O) after only 20 minutes of operation at 80 $m{\cdot}h^{-1}$, it could produce high-quality filtrates (with turbidity below 0.5 NTU). Therefore, it is expected that, if the available hydraulic load were higher, the longest filter could produce adequate filtrate (below 0.5 NTU) for an estimated period of about 60 minutes. It is important to emphasize that for all the studied filter runs, the apparent color values were below 1 CU, showing great color removal efficiencies even at high application rates.

In order to evaluate the different filters' performances, it is interesting to consider the applied filtration rates, which are attractive and promising characteristics of this kind of filter. It is evident that the 100-cm-long filters could work effectively for filtration rates as high as 80 $m{\cdot}h^{-1}$. Higher filtration rates could possibly be applied if a greater hydraulic load were available, as long as the limiting factor was not the quality of the produced water. Consequently, this work proved the efficiency of fiber filters made of polypropylene fibers for use at rates as high as 80 $m{\cdot}h^{-1}$.

The results obtained in this work were compatible with others found in the literature (Lee *et al.* 2006, 2008a, 2008b), even considering different construction methods, raw waters and coagulant dosages. Lee *et al.* (2006), for example, conducted experiments with 150-cm-long filters, whose filter beds were constructed with a porosity of 93%, using polyamide fibers with an average diameter of 30 μm. The authors used raw water with turbidity varying from 8 to 11.5 NTU. When applying filtration rates of 80 m/h and 1 mg/L of PAC, the authors could obtain filtrates within the turbidity limit of 0.5 NTU for 45 minutes.

This similarity can be associated with the analogous surface areas used by Lee *et al.* (2006) since the fiber diameters and the filter porosities were comparable. Therefore, the results of this part showed that flexible fiber filters can be adapted (changing filter media, for example) with satisfactory results and high rates compared with traditional sand filters, commonly operated at less than 15 $m{\cdot}h^{-1}$.

Despite the considerably different conditions adopted, it is also interesting to compare the results obtained in the present study with the ones found by Guerra *et al.* (2014) and Niu *et al.* (2015). Both studies evaluated the performance of shorter filters (40 cm long) applied to the clarification of high turbidity raw water (from 45 to 55 NTU), with and without the use of coagulant (PAC). Even though they could observe very high efficiencies (from 80% to 90%), no filtrate with less than 1 NTU was produced for the filtration rate either of 1,500 $m{\cdot}d^{-1}$ (about 65 $m{\cdot}h^{-1}$) or of

2,250 m·d^{-1} (about 95 m·h^{-1}). It is interesting to emphasize that in the study conducted by Guerra *et al.* (2014), no head loss was observed for the filtration rate of 1,500 m·d^{-1} (about 65 m·h^{-1}), whereas a head loss of about 1.65 mH$_2$0 was observed for 2,250 m·d^{-1} (about 95 m·h^{-1}), which is compatible with the values obtained in the present work.

In terms of suspended solid removal, the results obtained in the present work were similar to the best condition found by Lee *et al.* (2008a, 2008b), which corresponded to an efficiency of about 90% when using 1 mg·L^{-1} of PAC as coagulant. In the present research, efficiencies of 95% were obtained by the 60 cm filter operating at 40 and 80 m·h^{-1}, and of 90% by the 100 cm filter operating at 20 m·h^{-1}. Nonetheless, differently from the results obtained by Lee *et al.* (2006), a trend of increase in the retention of solids with the increase of the filtration rate was not detected in this study.

Regarding the coagulant adopted, the aluminum sulfate was selected due to its price and wider availability in Brazil, aiming to adapt the technology to other countries' contexts. Even though it was possible to show the feasibility of its use in flexible fiber filters, higher dosages were necessary to achieve the clarification goals, when compared with the studies using PAC. Aspects concerning materials availability, costs and environmental issues (e.g. sludge production) must then be considered for the selection of appropriate technologies in distinct countries.

Results of the fourth phase of experimental work

During this step, only the filters of 60 and 100 cm were evaluated, as these had shown better performance during the last phase of work. For the filter of 100 cm, mode 5 (operation of five stages, each consisting of the application of 3 seconds of air and 6 seconds of water in sequence) showed the best performance (initial pressure drop recovery and mass balance). On the other hand, backwashing modes 2, 3, 4 and 5 showed good efficiency for the filter of 60 cm. This fact shows the dependence of filter lengths on backwashing.

For both cases studied, mode 5 was chosen as the best backwashing condition, and water use was reduced in order to decrease losses during this step. Backwashing was again evaluated, applying mode 5 but reducing water flow to 300 m^3·m^{-2}·h^{-1}. For both filters analyzed, water flow reduction did not influence backwashing performance but reduced the percentage of water used during this step, to 3% and 2% for filters of 60 and 100 cm, respectively. These percentages are similar to the ones used for conventional sand filters, even though the backwashing process was not really optimized in this work. It is interesting to emphasize that high water and air flows can be applied to flexible fiber filters, as media loss does not occur in this configuration.

CONCLUSIONS

From this study, the following can be concluded:

- Flexible fiber filters built with polypropylene fibers can satisfactorily produce high-quality filtrates, and the results obtained are compatible with others conducted with polyamide fibers, with the benefit that polypropylene fibers are cheaper than the polyamide ones.
- Polypropylene filters with length as short as 25 cm could produce filtrate with less than 1.0 NTU at 20 m·h^{-1}. Filters with 60 and 100 cm could produce filtrate with less than 0.5 NTU operating at 40 and 80 m·h^{-1}.
- Polypropylene filters showed high productivity, with use of about 2% of water during the backwashing process.
- High water and air flows can be applied to this configuration of filters, which permits fast and effective backwashing.
- Color values were always below 1 CU for all filters during the filter run (before turbidity and head-loss limits were achieved), which shows the production of filtrates with high quality.
- The use of aluminum sulfate as coagulant was effective; however, its dosage was higher than the studies using PAC with similar raw water characteristics.
- Polypropylene fibers did not seem to release significant amounts of chemicals during the solubility assays; nonetheless, further studies are necessary in order to evaluate and quantify those compounds before polypropylene fibers are actually used as filter media for drinking purposes.
- The use of different fibers and coagulants in the construction and operation of this type of filter did not affect its performance, indicating that other materials could also

be used alternatively, in order to include available and/or natural resources.

For future work it is suggested to:

- evaluate the use of other fibers, such as the natural ones;
- assess the influence of the fiber's diameter on the performance of flexible fiber filters.

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