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Investigation of geometric properties of media particles and operating conditions on floating media filtration

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ABSTRACT

Filtration is an effective process in removing particles that are present in water. Floating medium filter has been used in direct filtration because of its flexibility, cost savings gained by less land requirements, and less water and energy required for backwashing. The aim of this work was to investigate the effect of geometric properties of a floating medium in up-flow filtration mode. A pilot plant was designed and constructed to evaluate the filtration process. Effect of physical parameters on filtration performance was also investigated. The experiments were carried out using a commonly available polypropylene floating medium. Four median grain sizes (2.28, 3.03, 3.30, and 4.07 mm) of polypropylene plastic pellets were used. Two media shapes (cubic and disc) were evaluated. Bentonite (250 mg/L ≈ 60 NTU) was used to make up the raw feed water. Three parameters that could influence the filtration performance were identified, namely: filtration velocity, media depth, and coagulant dose. The results showed that the best conditions to remove turbidity were found to be: low filtration rate (36.8 L/m^2 min), longer media depth (600 mm) and optimum coagulant dose (23 mg/L). The results also indicated that the smaller plastic medium (2.28 mm) was more efficient in terms of turbidity removal than the larger medium. However, headloss development associated with smaller media was higher (109 mm of water) than that associated with larger medium (42 mm of water).

Keywords: Filtration; Floating medium filter; Coagulation and flocculation; Water treatment

1. Introduction

Filtration is the most well-known method for removing clay and suspended solids (SS) from surface water. Slow sand filters and rapid sand filters are widely used for the removal of SS present in water, but sand filters have a number of limitations and drawbacks such as the limited retention capacity and high energy requirements for backwashing. One of the most serious problems involves maintaining bed homogeneity during operation. Inhomogeneities in the bed lead to formation of channels in the bed, poor distribution of the liquid flow through the bed, and thus very low particulate removal. Such inhomogeneities

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may also allow air to be trapped in the bed, also leading to the formation of channels and poor distribution of the liquid [1–3]. Over the past decade, many modifications have been made in efforts to minimize the shortcomings of conventional sand filters. Floating media filter (FMF) is one such modification.

2. Floating media filters

A FMF can be defined as a filter that is designed to use a floating medium such as expanded polystyrene or polypropylene or polyethylene in granulated or granular form that has a lower specific gravity than that of the water to be filtered. In such filters the floating medium is kept in a floating layer conditions and during filtration water flows vertically upward through the bed (a floating medium) [4–6].

FMFs differ from the conventional sand filters in many ways: the density of media particles is less than that of the water to be filtered; and a retaining grating is placed at the top of the filter in order to maintain the media inside the filter under submerged conditions [7,8].

It has been recommended that a FMF can be installed as a contact-flocculator and a pre-filter instead of using conventional processes for flocculation and sedimentation. The basic concept of a FMF involves the flow of suspension with flocculant through a packed bed of floating material to remove the flocs in the suspension. The flocculation process takes place during the contact of raw water and flocculant within the interstices of the medium, followed by the separation of particles and flocs by the filter medium [1,9,10].

A FMF was tested for the primary treatment of municipal sewage during dry weather and the high-rate treatment of combined sewer overflow during stormy weather. The medium that was used was a ring-shaped polypropylene net (diameter 2.2 cm, height 2.5 cm, and mesh size 6 mm). The removal rates of pollutants were 80–90% of SS and 44% of biological oxygen demand (BOD_5) under the following operating conditions 1,000 m/d flow velocity, and 2–3 mg/L of cationic polyelectrolyte concentration [11].

The objective of this paper is to determine whether the floating media particle size and shape have a significant effect on the performance of the FMF. Therefore, floating media of different sizes and shapes were investigated.

3. Experimental

3.1. Pilot plant

The schematic diagram of experimental set up is shown in Fig. 1. The filter column was made of clear PVC and had an inner diameter of 0.3 m and a height of 2.8 m. The filter consisted of three sections. The column cross-sectional area was 0.07065 m^2 and the volume was 0.164 m^3, for a water height of 2.32 m. The transparency of the column allowed observation of the media as the filtration process was in progress. A strainer plate was installed at the top to separate filtrate water and the packed media in the filter. The filter column had 10 piezometer taps at different levels. The distance between taps was 100 mm. Headloss was calculated as the difference between the head at each tap and the initial head. The flow was in the upward direction during the filtration process and downward direction for backwashing.

An artificial suspension of bentonite clay (fine granular sodium bentonite with an average particle size between 20 and 70 mesh, Chemical formula: $[(Na, Ca)_{0.33} (Al_{1.67} Mg_{0.33}) Si_4O_{10} (OH)_2 nH_2O)]$) and tap water (concentration 250 mg/L ≈ 60 NTU) was first prepared in a 20 L tank using a stainless steel high rate mixer. The mixture was stirred for 30 min and then the suspension was transferred from this tank to the raw water tank (1,500 L). The raw water in the feed tank was continuously stirred using a centrifugal pump while the pilot plant was in operation to prevent the SS from settling.

A centrifugal pump was used to mix the raw water into the feed tank in order to obtain a homogeneous solution. A mono pump, with a capacity of 900 L/h, was used to pump the raw water from feed tank into the plant for treatment. A flow meter (0−1,000 L/h) was used to measure the water flow in the FMF.

Chemical additions were dosed in-line. Ferric sulfate was used as a coagulant. The coagulant was pumped by using a dosing pump on-line to the system from the 20 L capacity storage tank. Suitable coagulant dosages were selected after carrying out a jar test. The optimum ferric sulfate dosage was 23 mg/L, at pH 5.5. The required dosage of ferric sulfate was introduced near the inlet of the filter. Immediately after the point of coagulant addition an orifice plate (diameter 12.5 mm) was installed in order to create a turbulent mixing flow. Thus, it served the purpose of a flash mixing device. A simple arrangement was provided for mixing at less turbulent condition by using a 25 mm diameter and a 9.5 m long flexible pipe in a spiral arrangement. This simulated the same principles described for the jar-testing procedure, rapid mixing at maximum turbulence for a very short period of time at the orifice point to effect coagulation, and then slow mixing for a longer period of time at the spiral flexible pipe to effect the flocculation process by thickening of the flocs before they enter the filter column.

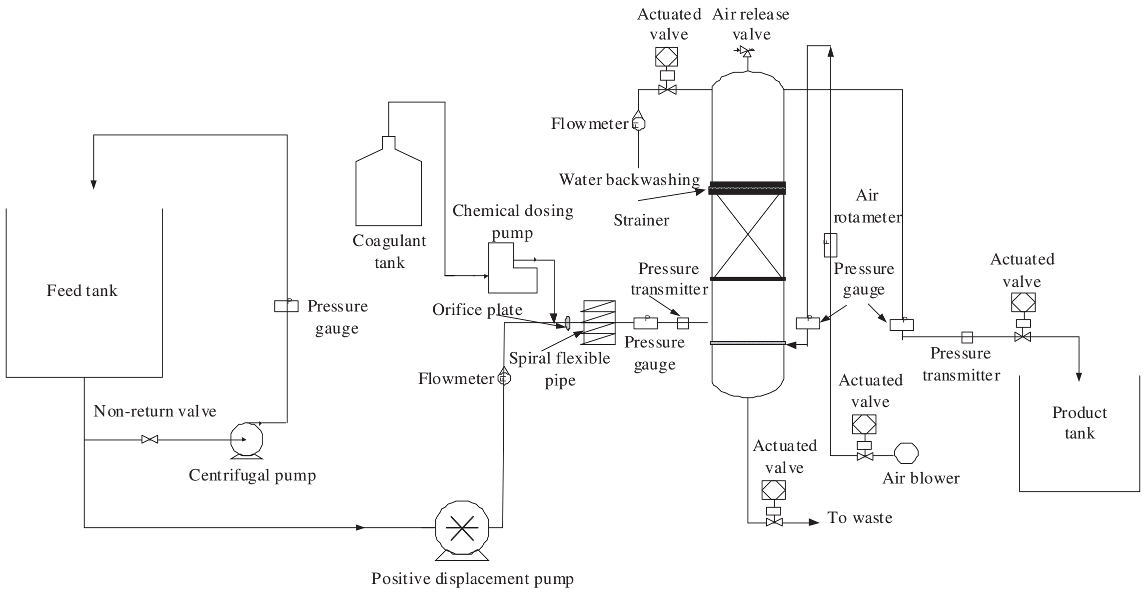

Fig. 1. Schematic diagram of the upflow floating media filtration unit designed for use in this study.

3.2. Experimental conditions

The system was operated at different filtration rates, different media depths, and coagulant doses. The filtration rates of 2, 3, and 4 m^3/m^2 h were examined. Media depths of 0.2, 0.4, and 0.6 m were tested. Coagulant doses of 50, 75, and 100% of the optimum dose were examined. Experimental conditions (filtration rates and media depth) were selected due to available experimental facilities. Feed tank volume constrained the experimental design. This only allowed a maximum of 312 L/h (filtration rate) of feed water to be pumped to the filtration system. In addition, any rate above this value would not have allowed an effective assessment of all other parameters involved considering the associated reduction in the operational period. The limited experimental materials (floating media) dictated the choice of the levels of media depth. The available materials only allowed a maximum depth of 600 mm.

Experiments were conducted using five floating media (Fig. 2). Polypropylene beads were used because this polymer is commercially available in South Africa. One media combination was used to determine its effect on turbidity removal and to confirm the effect of media size on FMF performance. Three experiments were conducted using the media combination: 75% (w/w) plastic beads (media (ii)) and 25% (w/w) LLDPE powder (media (v), $d_{50} = 600\ \mu m$). A summary of the operating conditions of the experiments is presented in Table 1.

The pilot plant performance was assessed by determining the filtrate quality and the efficiency of the filter bed. The filtrate quality was measured in terms of turbidity, while the efficiency of the filter bed was examined by determining the headloss development along the filter bed.

4. Results and discussion

The performance of FMF was examined using different media (Fig. 2) at different operating conditions. Table 2 shows the performance of different floating media in terms of turbidity removal and headloss development. It could be seen clearly from Table 2 that combined media and media (v) could produce filtrate at low turbidity of 0.14–0.22 NTU and higher water production with high headloss development of more than 500 mm.

4.1. Effect of physical parameters

4.1.1. Filtration rising velocity

Three different filtration rising velocities were tested for all types of media in this study. At filtration velocity of 2 m/h, the filter run time as well as water production rate is higher than the other filtration velocities for all media. In general, the filtration velocity of 2 m/h gave a better result in terms of turbidity removal, water production, and filter run time for all types of plastic media. The performance

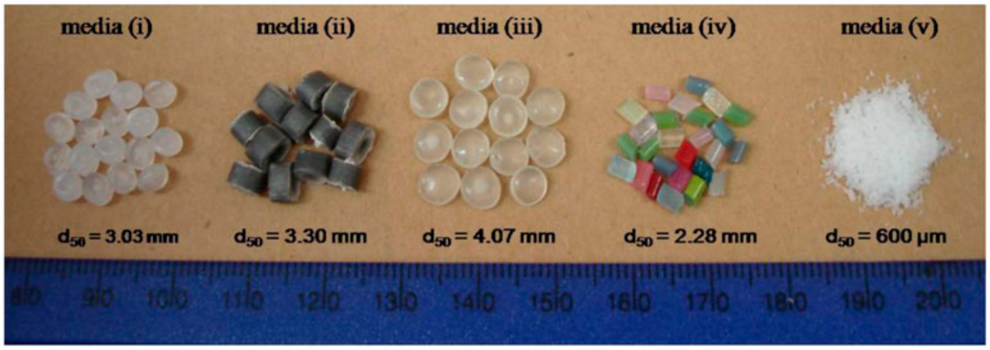

Fig. 2. Different sizes and shapes of plastic media that were tested in this study. From left to right: smooth cubic (media (i)), large cubic (media (ii)), disc (media (iii)), small lice-cut cubic (media (iv)), and LLDPE powder (media (v)).

Table 1
Operating conditions of the experimental runs

Experimental run	Filtration velocity (m/h)	Media depth (m)	Chemical dosage (mg/L)
1	2	0.2	11.50
2	4	0.2	11.50
3	2	0.6	11.50
4	4	0.6	11.50
5	2	0.2	23.00
6	4	0.2	23.00
7	2	0.6	23.00
8	4	0.6	23.00
9	3	0.4	17.25
10	3	0.4	17.25
11	3	0.4	17.25

Table 2
Performance of different floating media at different operating conditions

Medium	Experimental run	Breakthrough time (h)	Lowest turbidity achieved (NTU)	Maximum headloss at breakthrough (mm)	Water production (L)
Media (i)	Run 2	2	1.73	11.3	312
	Run 4	3	0.83	41.5	624
	Run 8	3	1.03	34.5	624
Media (ii)	Run 1	3	1.66	16.5	312
	Run 5	4	0.79	11	468
	Run 8	3	0.43	57	624
Media (iii)	Run 1	4	1.34	15.5	312
	Run 3	6	0.84	35.3	780
	Run 8	2	0.97	42.2	312
Media (iv)	Run 2	2	1.14	65.2	312
	Run 4	3	0.57	109	624
	Run 5	5	0.42	48	624
Media (v)	Run 6	–	0.22	>400	936
	Run 7	–	0.14	>500	936
Combined media	Run 4	–	0.147	299	1,248
	Run 7	–	0.16	233.5	936

for all types of media at different velocity is shown in Figs. 3 and 4.

At low flow velocity, bridges of particles are formed due to low inertia and long retention time. This results in higher particle removal and longer filter run time. The increase in flow velocity brings about high drag forces leading to the increase in pressure drop. This interpretation is supported by some previous studies [12–14].

As shown in Figs. 5 and 6, the headloss increased with increase of filtration velocity in all types of media. During the filtration run time, the increase in the filter headloss was almost linear with respect to filtration time. This indicates that particle removal (filtration) took place within the depth of the filter bed. As evident in Figs. 5 and 6, the headloss is distributed over the whole depth of the filter indicating that particles/flocs are able to penetrate deep into the media depth. The same trend was reported by other studies [15–19].

4.1.2. Media size and shape

As expected, experiments in which the smaller-size media (media (iv), diameter 2.04 mm) were used gave better results than when the larger size (media (ii) and media (iii)) were used. This finding is consistent with this of Werellagama [20].

It can be clearly observed from Figs. 5 and 6 that headloss through granular media was shown to be sensitive to the size of the media since the headloss was much higher when small size media (media (iv)) was used. However, there was no significant difference in the headloss between media (i), and media (ii) as there was no big difference in their sizes. On the other hand, media with cubic shape ((i) and (ii)) gave better results than media with disc shape (iii). A typical result is also shown in Figs. 3 and 4, where media in two different shapes are compared. These experimental results reveal that cubic polypropylene media ((i) and (ii)) performs better than disc-shaped media (iii). A filtrate turbidity of <1 NTU was achieved when cubic media were used, whereas when media (iii) (disc-shaped) were used the filtrate turbidity was >1 NTU. Considering headloss development, the headloss in the case of disc-shaped media was relatively lower than that of cubic-shaped media.

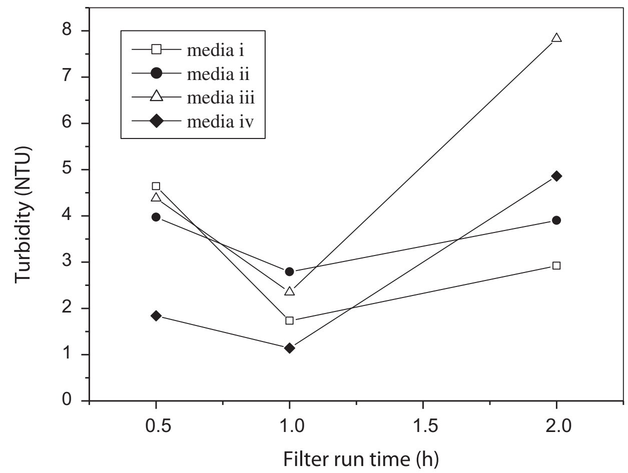

Fig. 4. Effect of filter run time vs. turbidity for all different media (filtration velocity 4 m/h and media depth 200 mm).

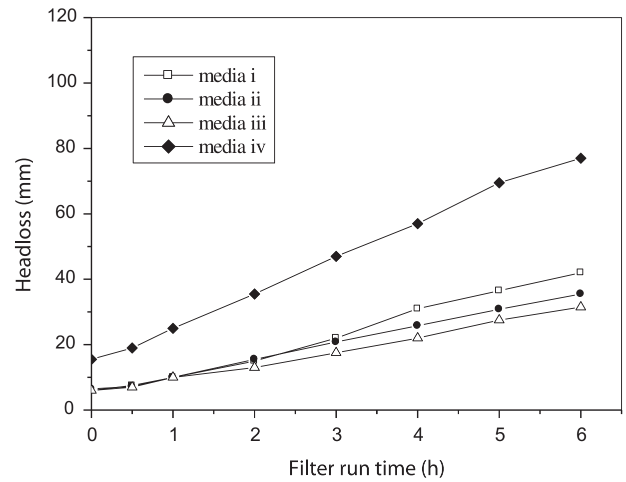

Fig. 5. Headloss vs. filter run time for all different media (filtration velocity 2 m/h and media depth 600 mm).

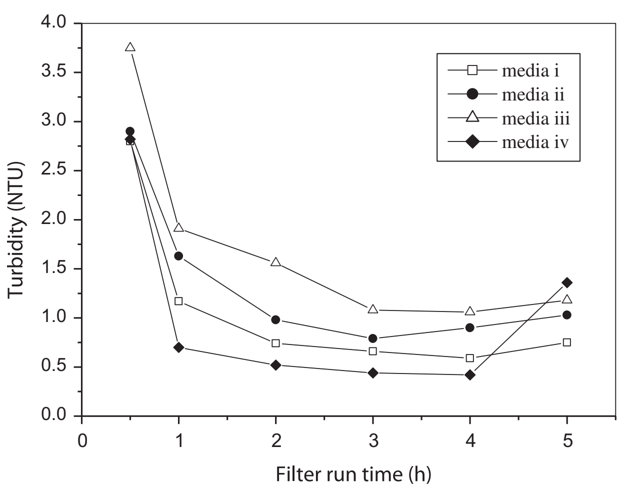

Fig. 3. Effect of filter run time vs. turbidity for all different media (filtration velocity 2 m/h and media depth 200 mm).

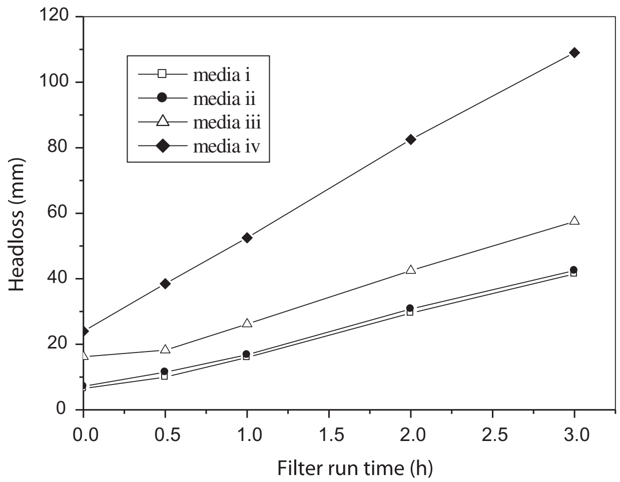

Fig. 6. Headloss vs. filter run time for all different media (filtration velocity 4 m/h and media depth 600 mm).

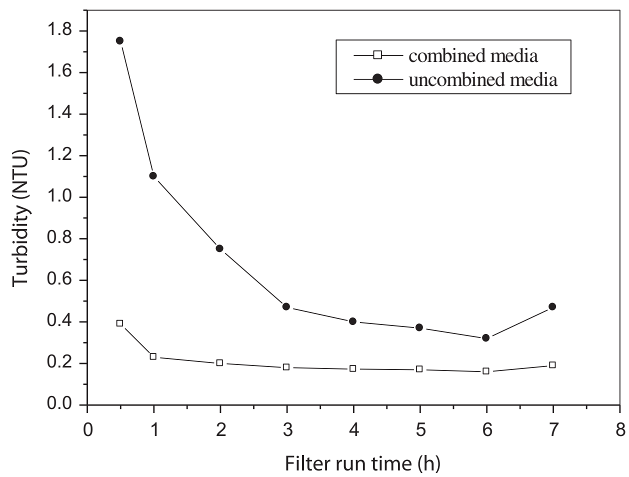

Fig. 7. Comparison of use of combined media and uncombined media (filtration velocity 2 m/h, media depth of 600 mm, and chemical dose 23 mg/L).

4.1.3. Media combination

The results of using dual media (plastic beads: LLDPE powder, 75%: 25%) were significantly improved in terms of filtrate turbidity and water production. However, the headloss was much higher than when plastic beads (media (ii)) alone were used. A summary of the obtained results is tabulated in Table 3. Figs. 7 and 8 show the results of the above combined media ((ii) and (v)), compared with uncombined media (media (ii)) in terms of filtrate turbidity and headloss development.

Fig. 8 clearly shows that headloss development was very low with uncombined media compared to the combined media. The highest headloss was observed with the combined media at high filtration velocity.

It can be concluded that the filtrate quality improved in combined media due to the powder was distributed evenly throughout the coarser media.

Table 3
Summary of combined media results

Experimental trial	7	8
Filtration velocity (m/h)	2	4
Media depth (mm)	600	600
Maximum headloss development (cm)	22.55	33.25
Lowest NTU achieved	0.16	0.18
Filter run duration (h)	6	4
Water production (L)	936	1,248

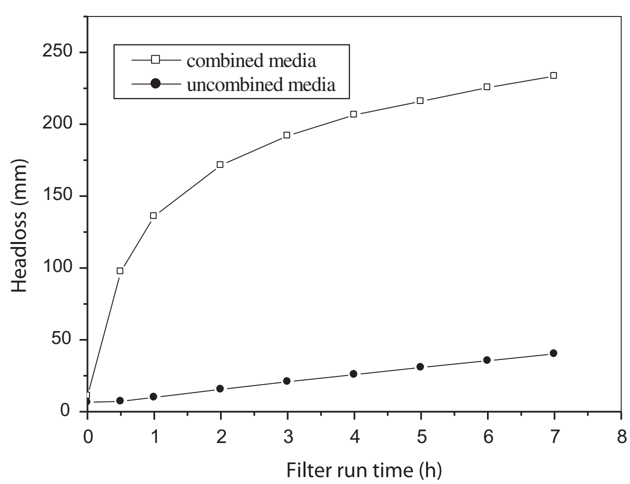

Fig. 8. Headloss development of combined media and uncombined media (filtration velocity 2 m/h, media depth 600 mm, and chemical dose 23 mg/L).

4.1.4. Headloss variation along the filter bed

To study the headloss variation along the filter media, a number of piezometer tapping points were connected at different positions along the filter bed. The headloss development along the filter is presented in Figs. 9–11 for different conditions. The location of the piezometer tapping points in the filter is also shown. In the case of media depth of 200 mm piezometer points 8 and 9 were connected to the filter bed while piezometer points 7 and 10 were connected below and above the filter bed, respectively. In the case of media depth of 600 mm piezometer points 4–9 were connected to the filter bed while piezometer

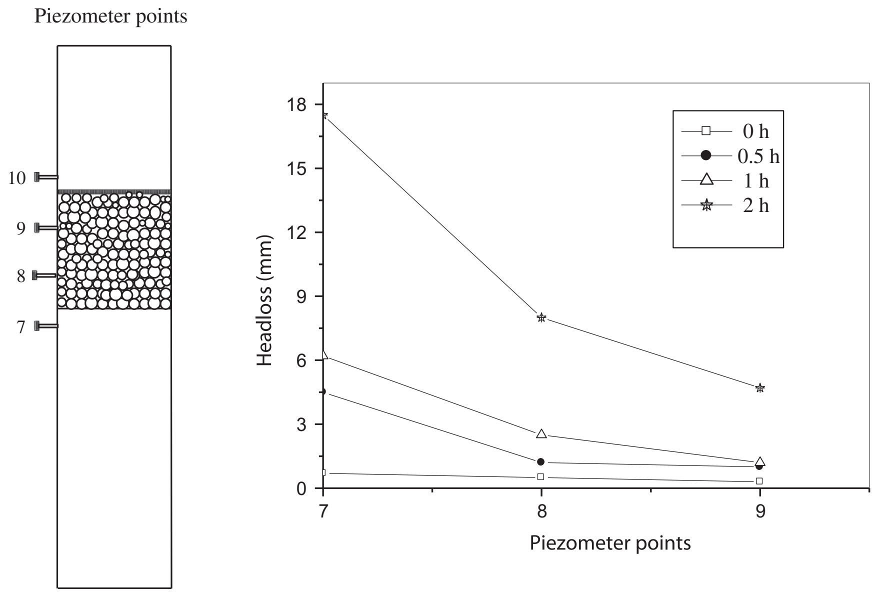

Fig. 9. Headloss profile of media (iii) (filtration velocity 4 m/h, media depth 200 mm, and chemical dose 23 mg/L).

points 3 and 10 were connected below and above the filter bed, respectively.

As shown in Fig. 9, the particle removal process was taking place in the entire filter bed. Most of the removal was achieved in the bottom layer below point 8 and that can be deduced from the observed higher headloss difference between point 7 and point 8 in comparison with point 7 and point 9. In the case of media depth of 600 mm, and as it can be observed from Fig. 10, most of the particle removal was achieved in the area between point 3 and point 6 and as the flow went up there was no remarkable particle removal. This showed that most of the flocs / particles were retained in the layer between 3 and 6 with no or very little penetration of flocs in the upper layers (above point 6). Headloss also seemed to be stabilized in this area.

In the case of combined media, and as shown in Fig. 11, a significant increase in headloss development took place starting around the 30th minute of operation. This indicates that most of the contaminant removal was achieved at the bottom region of the bed at a very early stage of filtration.

It can also be observed from Fig. 11 that the filtration process (particle removal) occurred in the first three hours since the headloss difference in the first three hours period is about fivefold higher than the second three hours period.

4.1.5. Backwashing

Most of the experimental runs were done using plastic granules; backwashing was done by air backwash followed by water backwash. The total media expansion was 100% in most of the plastic granules that were tested. It was observed that all the plastic granules used in this study were well agitated during backwashing. This leads to a very high amount of detachment of the captured particles which drops down from media during air backwashing.

It was also observed that backwashing with water only did not agitate the media, and as a result of that only small amount of contaminants were released from the media, which means longer time is needed for cleaning.

The backwashing performance is compared in terms of water required for the backwashing. The criterion for the backwash performance is that the turbidity of the effluent water should be as close to the influent water as possible. It was observed from backwashing process that backwash with air followed by water required less water than backwash with water only, because most of the captured flocs were detached from the media during the air backwash. This phenomenon was visually observed during the air backwash. A further observation is that in some of backwashing runs were done in this study backwash with air followed by water required half the amount

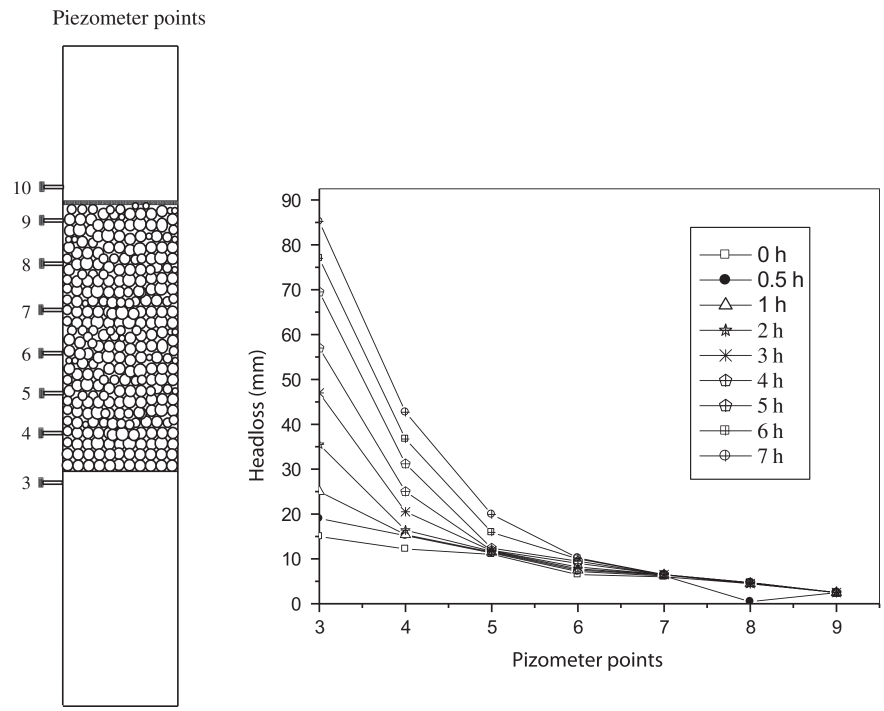

Fig. 10. Headloss profile of media (ii) (filtration velocity 2 m/h, media depth 600 mm, and chemical dose 23 mg/L).

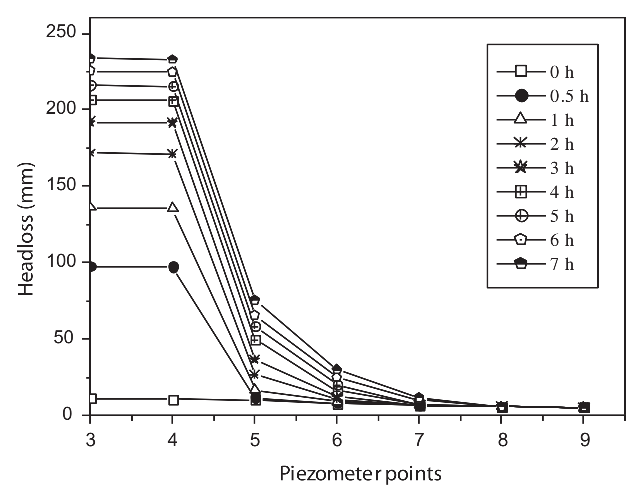

Fig. 11. Headloss profile of combined media (filtration velocity 2 m/h, media depth 600 mm, and chemical dose 23 mg/L).

of water than that used in backwash with water only to achieve the same backwash effluent quality.

5. Conclusions

In this study, three factors that could possibly affect the filtration process were investigated. These included the filtration rate, the filter bed depth, and the chemical coagulant dosage. The best conditions to remove particles (turbidity) were found to be: (1) filtration rate at 36.8 L/m^2 min, allowing slower clogging interstitial spaces within the medium grains and hence longer filter run time, (2) filter bed depth of 600 mm, allowing particles to have the opportunity to potentially interact with more medium grains, and hence the chance for particle attachment to and within media grains, and (3) chemical coagulant dosage of 23 mg/L, allowing a greater number and bigger size of flocs to be formed.

Decreasing the medium size increases the surface area and tortuosity of the filter bed, while decreasing the interstitial spaces within the medium grains. All these factors led to increase the turbidity removal as it was observed with the smaller medium (2.28 mm). Filtrate quality with 0.4 NTU was achieved by using medium size of 2.28 mm and voidage of 0.31. However, the increase in removal efficiency is counterbalanced by an increase in the headloss development. Headloss development experienced by the smaller medium was higher (109 mm of H_2O) than that experienced by the three other media (42 mm of H_2O). Both headloss readings were at breakthrough time.

Results and experimental observations of headloss development along the filter bed showed that the effective bed depth (the minimum depth that produces the best water quality of filtrate) reduces with reduction in effective medium size. The effective bed depth for the smaller medium (2.28 mm) was ≈0.2–0.3 m of 0.6 m depth, while the effective bed depth for the three other media (3.03, 3.30, and 4.07 mm) was greater than 0.3 m. These findings suggest that larger-size medium and greater depths might be a more optimal filter design from the standpoint of turbidity removal and headloss development.

Shape of medium grains leads to various grain packing, which changes the liquid flow through the filter bed. The more compact the filter bed the less the voidage, the better the particle removal. Although the size of media experimented in this study was inconsistent, the shape of some media such as medium (ii) (angular medium) led to better performance compared to medium (iii) (smooth disc-shaped medium). Angular granular medium grains result in low filter bed voidage (0.36) as they can readily interlock. However, these findings should be further investigated with consistent medium size in order to confirm the aforementioned conclusion.

Fine media combined with coarse plastic media was difficult to backwash. Another major difficulty associated with combined media was the loss of the fine medium during the backwashing.

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