Multi-stage polyurethane foam filtration for emergency point-of-use water treatment

Sarah Levine[1], Michael J. Adelman[1,3], Rachel B. Philipson[1,4], Kelly R. McBride[1,5], Bradshaw N. Irish[1], Sarah C. Stodter[1,6], and Monroe L. Weber-Shirk[2]

[1]Students and [2]Senior Lecturer, School of Civil and Environmental Engineering, Cornell University, Ithaca, NY, email: mw24@cornell.edu, phone: (607) 216-8445 (corresponding author)
Current affiliations: [3]Engineer, MWH, Arcadia, CA; [4]Engineer, Woodard & Curran, White Plains, NY; [5]Analyst, Medallia, Inc., Palo Alto, CA; [6]Engineer, ENVIRON, Los Angeles, CA.

ABSTRACT

There is a global need for technologies that can treat high-turbidity surface waters to provide safe drinking water for rapid deployment in emergency situations, and also for very small communities, schools, and hospitals. This paper presents a multi-stage filtration process based on a novel depth filtration application of polyurethane foam. Laboratory characterization of low-density, highly porous polyurethane foam revealed depth removal capabilities for both roughing and finishing filtration. This filter medium was characterized in a bench-scale apparatus by varying approach velocity, filter depth, pore size, head loss, and influent turbidity. In the presence of a coagulant, successful roughing filtration was achieved with 30 ppi (pores per inch) foam, while finer 60 or 90 ppi foams served as effective finishing filters. The cleaning cycle, in which the foam is squeezed to remove the entrained contaminants, was also demonstrated. A prototype multi-stage emergency treatment unit was constructed, including coagulant and disinfectant dosing along with roughing and finishing filters. This system produced potable water with influent turbidities up to 1000 NTU at a high approach velocity of 6 mm/s.

Keywords: multi-stage filtration, emergency treatment, polyurethane foam, point-of-use

INTRODUCTION

The World Health Organization (WHO) reports that 1.73 million deaths each year can be attributed to poor sanitation and water treatment, indicating a global need for robust and reliable water treatment technologies (Howard, 2003). This need is even more pronounced in developing countries with poor infrastructure and in situations where a country's infrastructure is compromised by a natural disaster or large-scale emergency. Specifically in emergency engineering, adequate water treatment is essential for prevention of disease outbreaks following a disaster. For example, diarrheal diseases cause an estimated 40% of deaths in refugee camps, and 80% of these cases occur in children under two years of age (Doocy and Burnham, 2006). In extreme cases, diarrhea can cause up to 85-90% of refugee camp mortality, as in the 1994 crisis in Rwanda (Toole and Waldman, 1997). Existing technology is not always adequate for responding to public health needs in the wake of a disaster. For example, after the South Asian earthquake of 2005, the systems intended for emergency water treatment could not be cleaned well enough to consistently provide potable water (Dorea, 2007).

Emergency water treatment is not only necessary in situations overseas where infrastructure may be limited; a technology for rapid and reliable water treatment following a natural disaster could help save lives in the U.S. as well. For instance, after Hurricane Katrina, vital existing infrastructure including water treatment plants and pipe distribution networks were damaged, and thus flood waters were heavily contaminated with untreated sewage. Without electricity, many drinking water and wastewater facilities were inoperable. An estimated 1,220 drinking water systems were affected, depriving thousands of safe water (Copeland, 2005).

There is a great need for a technology that can quickly provide a safe drinking water supply following a natural disaster at a low cost. Such a device would need to be: easily transported to disaster sites or refugee camps; capable of performing reliably even without electricity or stable infrastructure; simple to operate; and able to treat a large flow rate with a relatively small equipment requirement. Additionally, the unit should be affordable and built in-country from local materials.

Foam filtration is a form of depth filtration where reticulated polyurethane foam is used as a filtration medium. While polyurethane foam is commonly employed in air filters, there have been only a few studies that used foam in water filtration (Jain and Pradeep, 2005; Sartory et al., 1998). These prior studies focused primarily on foam coated with a disinfectant such as silver nitrate, and were more concerned with bacterial removal than treatment of turbid water. However, turbidity removal is also a potential application of foam filters. Surface waters may be highly turbid, and common chemical disinfectants like chlorine are only effective when turbidity is below about 5 NTU (Lechevallier et al, 1981). If foam filtration is effective as a turbidity removal process, it could be used in conjunction with disinfection (such as by chlorination) to produce potable water from a highly turbid source such as a river. In addition, as a lightweight, relatively inexpensive, and widely-available material, foam would be well-suited to emergency point-of-use treatment. Beyond its potential application in emergencies, foam filtration may also be suitable for providing safe drinking water to small communities or small-scale water users that otherwise lack an affordable means of treatment.

The objectives of this study were: (1) to characterize polyurethane foam on the laboratory scale as a medium for depth filtration, and (2) to develop and test a prototype emergency water treatment system using foam filters.

MATERIALS AND METHODS

Characterization studies. An extensive study using a bench-scale apparatus was conducted in order to better characterize the performance of polyurethane foam as a filtration medium. A schematic of this apparatus is presented in Figure 1.

Aerated tap water was dosed with a concentrated kaolin clay suspension to provide constant influent conditions. The turbidity and temperature were controlled by laboratory process control software based on readings from an in-line raw water turbidimeter and a thermistor. Water was pumped from the raw water tank to the filter column, where the desired amount of polyaluminum chloride (PACl) coagulant was introduced into the raw water line using a computer-controlled peristaltic pump. Rapid mix was assumed to occur over the 100 cm of 4.8 mm inner diameter tubing, and no subsequent flocculation or sedimentation processes were used.

The filter apparatus was composed of a 1-inch diameter glass column approximately 2 feet in length. The foam bed consisted of several foam cylinders about one inch in height and

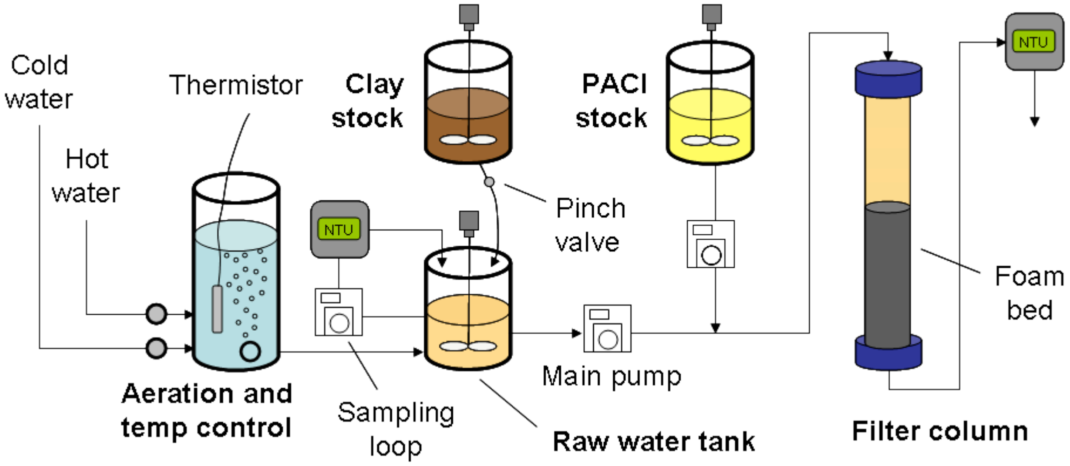

FIGURE 1. Diagram of the bench-scale foam filtration apparatus.

slightly larger than one inch in diameter. It was necessary to cut each foam cylinder slightly larger than the diameter of the glass tube to compress the foam against the wall of the column and prevent preferential flow paths. Care was taken when placing the foam cylinders in the column to ensure that no air bubbles were caught in the filter.

The filter beds consisted of SIF-brand fully reticulated polyurethane foam (Reilly Foam Corp., Eagleville, PA). Three pore sizes of foam were evaluated for their filtration properties: 30, 60 and 90 pores per inch (ppi, a linear measurement). In addition to varying foam pore size during experimental trials, other process variables were tested including approach velocity, foam bed depth, influent turbidity and coagulant dose.

Prototype treatment system. The prototype was designed as a multi-stage depth filtration process contained in two filtration columns. The prototype consisted of a roughing filter composed of 30 inches of 30 ppi foam and a finishing filter with 15 inches of 90 ppi foam. The rouging filter removed larger particles as well as aiding in flocculation. The finishing filter removed smaller particles and reduced the turbidity to appropriate standards. Multi-stage filtration reduces the load on the finishing filter, thereby increasing the run time before the finishing filter requires cleaning. Additionally the large pores of the roughing filter allows for higher turbidities to be treated by the filter than would be treated through a finishing filter alone.

In addition to the filtration columns, the prototype also contained a flow control valve, a submersible pump, raw water tank, and coagulant dosing tank. The submersible pump and flow control valve were used for experimental purposes only, to maintain a constant flow through the system. Coagulant concentration was calculated based on the fixed flow rate and fixed influent turbidity. The coagulant was dosed into the influent water using the gravity-powered chemical dosing system described by Swetland et al. (2012). The system included a chemical stock tank feeding a constant head tank, with a linear flow orifice meter that adjusts the position of a drip tube based on the incoming flow rate so that a constant coagulant dose is maintained. This system represents a robust chemical dosing method for emergency treatment.

Experiments with the prototype apparatus studied the turbidity removal performance and cycle time of the filter system under varying influent conditions. The foam cleaning process was also tested at the prototype scale.

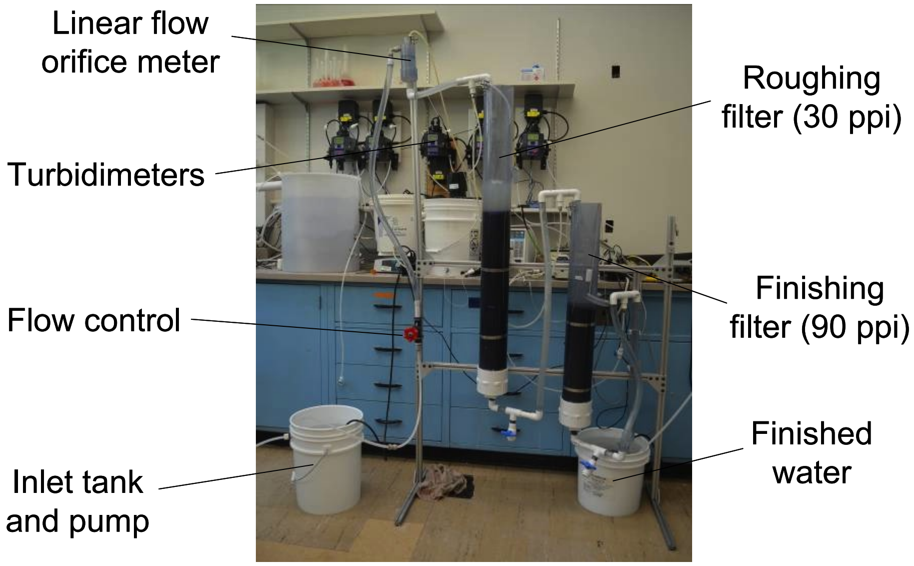

FIGURE 2. Photo of the treatment system prototype apparatus.

Data acquisition and analysis. For both the bench-scale and prototype experiments, removal of suspended solids was quantified with Micro-TOL in-line turbidimeters (HF Scientific, Ft. Meyers, FL). Based on turbidity measurements, the performance of a given filter can be expressed as log removal, *pC**, calculated using Equation (1):

$$pC^* = -\log\left[\frac{T_{Effluent}}{T_{Influent}}\right] \qquad (1)$$

where $T_{Effluent}$ is the effluent turbidity in Nephelometric turbidity units (NTU) and $T_{Influent}$ is the influent turbidity (NTU). Head loss was also measured in both the bench-scale and prototype-scale experiments using PX26 electronic differential pressure sensors (Omega Engineering, Bridgeport, NJ). All data was logged electronically using the laboratory process control software that also controlled the raw water temperature, influent turbidity, and peristaltic pump flow rates.

RESULTS AND DISCUSSION

Foam imaging and characteristics. The foam medium was photographed using scanning electron microscopy (SEM) to determine its pore-scale geometry (see Figure 3).

Unlike in granular filter media where pores are the void space between discreet solid particles, the porosity of polyurethane foam results from the three-dimensional structure of skeletal strands that form interlinked 6-sided polygons. It is also noteworthy that the pores make up the vast majority of the total volume of the foam. This is consistent with expectations from the literature: Armentia and Webb (1992) report a porosity of 0.97 for 80 ppi polyurethane foam.

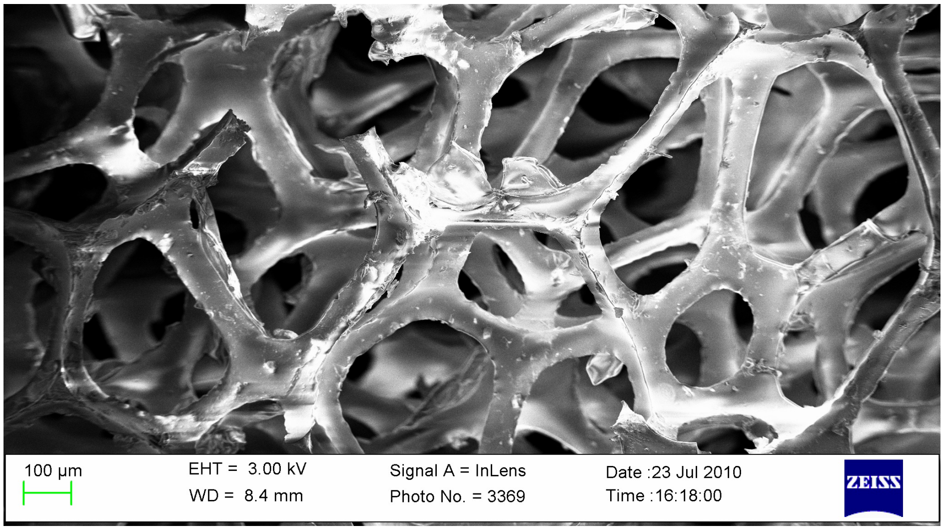

FIGURE 3. SEM image of 90 ppi polyurethane foam.

The highly porous nature of foam implies that it can be loaded at even higher approach velocities than other high-rate filter media. The actual interstitial or pore velocity V_{Pore} in a porous medium is the approach velocity V_a divided by porosity ε:

$$V_{Pore} = \frac{V_a}{\varepsilon} \qquad (2)$$

Equation (2) shows that as porosity increases, approach velocity can increase proportionally and still maintain a constant interstitial velocity. Because the porosity of foam is about 2 to 3 times that of filter sand (typically 0.35 to 0.47), allowable approach velocities for foam filters should be about 2 to 3 times the maximum loading rate for rapid sand filters.

Approach velocity optimization. Determination of the optimal approach velocity for a polyurethane foam filter is essential to the eventual design and operation of a filter unit. In order to better quantify the relationship between approach velocity and filter performance, a 90 ppi foam core sample at a filter depth of 24.5 cm was tested for approach velocities of 3, 6, 12, 18, 24 and 38 mm/s with a constant influent turbidity of 5 NTU and constant alum dose of 1.5 mg/L. These conditions were chosen to represent clarified water from an upstream sedimentation tank or roughing filter; however, the relationships between approach velocity and filter performance are assumed to be the same with varying influent conditions.

Figure 4 shows the average effluent turbidity over the course of each filter run for varying approach velocities. The 38 mm/s approach velocity is not shown because it was not effective in removing colloids. A pC^* of 2.4, 1.8 and 1.4 was achieved for approach velocities of 3, 6, and 12 mm/s, respectively. As expected, filtration performance decreases with increasing approach velocity. At higher velocities, the velocity gradient within the pores of the filter bed becomes more steep, which likely causes particles previously entrained in the filter to shear off and end up in the filter effluent.

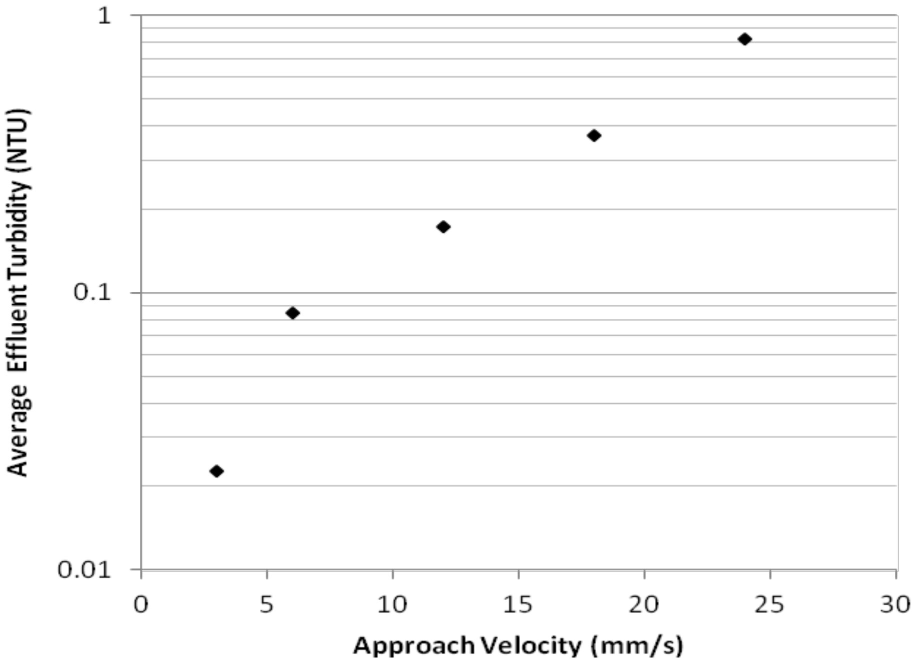

FIGURE 4. Effluent turbidity at varying approach velocity, with 5 NTU influent.

A *pC** of around 1.6 is expected for turbidity removal in conventional rapid sand filtration with a typical approach velocity of 2 mm/s and a bed depth between 0.5 and 0.75 m (Reynolds and Richards, 1996). The results in Figure 4 show that foam with an average approach velocity 2-3 times faster than typically found in rapid sand filtration can achieve similar performance. Additionally, this performance is achieved in a foam filter with approximately half the bed depth required for rapid sand filtration.

Based on this study, an approach velocity of 6 mm/s (8.8 gpm/ft^2) was selected for additional experimental trials and the design of a foam filter apparatus. This approach velocity was selected to optimize both filter unit surface area and performance. Lower design approach velocities yield diminishing returns on increased performance, while increasing the size of the filter unit. While a higher design loading rate of 12 mm/s would likely yield satisfactory filter performance, a lower approach velocity was selected to incorporate a factor of safety against turbidity breakthrough.

Filter depth and influent turbidity. Filter performance with respect to bed depth was tested using 30 ppi foam over three depths: 12.7 cm, 25.4 cm and 38.1 cm, at an approach velocity of 6 mm/s, with 100 NTU influent and 30 mg/L coagulant dose. Figure 5 presents normalized filter performance (*pC** per m of bed depth) as a function of time for the three filter bed depths tested.

The three performance curves are of similar form, showing initially improved particle removal akin to the ripening process observed in sand or mixed media filters, followed by declining particle removal as pores fill in the filter medium. The fact that *pC** scales linearly to bed depth for foam filters is consistent with depth filtration theory, and provides evidence that foam filters work by a depth filtration mechanism. This relationship between filter bed depth and *pC** is also important in designing a filter to achieve a desired level of performance.

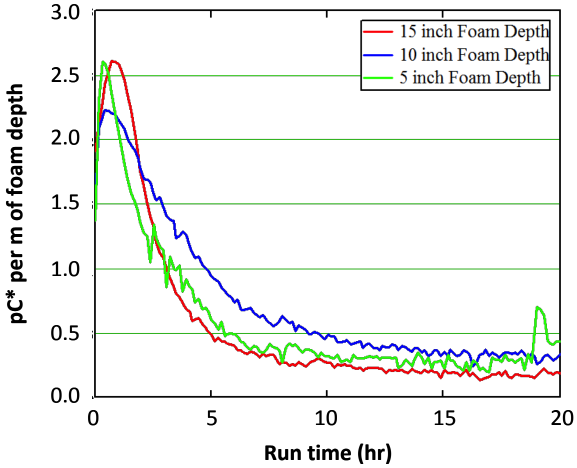

FIGURE 5. *pC** per unit depth for three roughing filters.

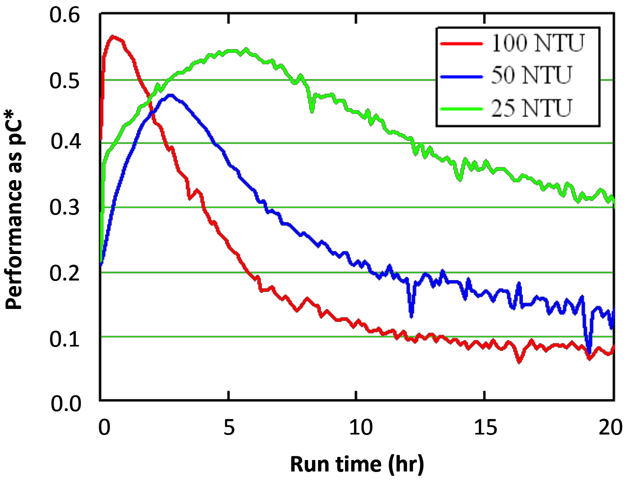

FIGURE 6. Roughing filter performance at three influent turbidities.

In addition to varying filter depth, influent turbidity was also varied in order to characterize filter performance over a range of potential conditions. The filtration performance of 30 ppi foam was tested with influent turbidities of 100, 50 and 25 NTU. Coagulant dose was varied linearly with increasing turbidity, such that the same fraction of particles would receive exposure to the coagulant.

Results from these trials are presented in Figure 6. All three turbidities have similar peak removal rates; however, with increasing turbidity, the length of time at which the removal rate can be sustained decreases. Additionally, the peak removal rate is achieved in less time with higher influent turbidities. This is consistent with the expectation that filter ripening would occur more quickly with a higher solids loading to the filter.

Prototype treatment system performance. The prototype was tested for influent turbidities ranging from 100 to 1000 NTU, as documented in Table 1. The filters were operated with an approach velocity of 6 mm/s and a flow rate of 2.9 L/min. For these trials, the filter was run to breakthrough, defined as the point when the effluent turbidity exceeded the U.S. EPA standard of 0.3 NTU. The filter consistently reduced effluent turbidity well below this standard for all influent turbidities, for varying lengths of time. In each case, the filter provided exceptionally clear effluent, 0.01 to 0.04 NTU, for roughly half the test duration. This was generally the length of time required for the roughing filter to reach breakthrough, shifting the burden of particle removal to the finishing filter. The 100 NTU tests either reached breakthrough or, more often, exceeded the maximum allowable head loss after an average 7.5 hours. The 200 and 450 NTU tests reached breakthrough after 1.5 to 3 hours, and the 1000 NTU test lasted 50 minutes.

Exemplary performance data is shown in Figure 7. The overall average *pC** for all trial runs ranged from 2.8 to just over 4, reaffirming the effective performance of the filter. Head loss patterns were recorded for each test to determine the effectiveness of the filter cleaning cycle and to monitor the foam's long-term performance. Head loss in the roughing filter increased linearly for the entire duration of the test, as expected for depth filtration. In the finishing filter, head loss accumulated slowly until the roughing filter reached breakthrough, then built up quickly. After each cleaning cycle, the head losses in the roughing and finishing filters

TABLE 1. Summary of test results for the prototype apparatus.

Experiment	Influent turbidity (NTU)	Run time to breakthrough	Terminal head loss (cm) Roughing	Terminal head loss (cm) Finishing	Average system *pC**
1	100	7h 5m	44.0	20.6	3.71
2	100	8h 9m	49.0	12.0	3.75
3	100	8h 4m	44.6	13.9	3.32
4	200	2h 3m	20.0	22.0	2.83
5	200	3h 31m	30.7	29.5	3.62
6	450	2h 6m	34.0	23.4	4.01
7	450	1h 23m	25.6	11.1	4.02
8	450	1h 25m	27.2	10.5	4.02
9	1000	50m	20.7	10.9	4.05

returned to clean bed heights, demonstrating the cleaning cycle's ability to return filter performance to pre-test levels. Head loss accumulation was examined as a possible indicator for when the filter required cleaning. Unfortunately, terminal head loss associated with breakthrough varied with influent turbidity, suggesting it might not be an appropriate indicator.

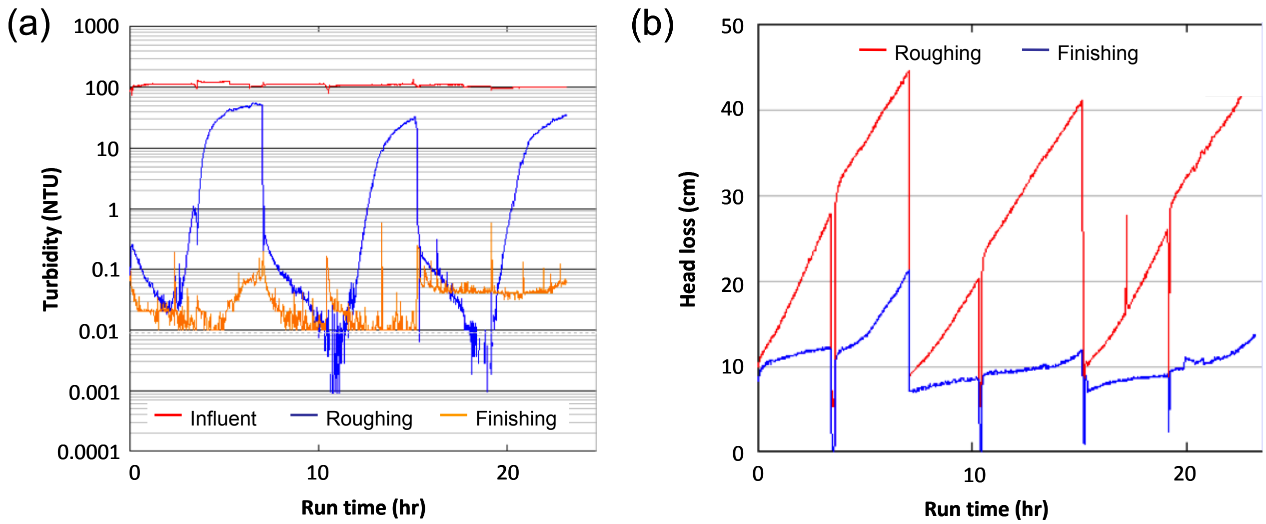

FIGURE 7. Example data from a prototype-scale experiment, showing (a) filter performance and (b) head loss accumulation.

Cleaning cycle. The foam filter beds are cleaned in-column in much the same way that one would compress a dirty dish sponge to release entrained particles. Flow to the apparatus does not stop while a column is being cleaned, but both the wastewater produced from flushing the foam column and the treated water from the apparatus should be drained during this cycle.

A plunger has been designed which consists of a long pole with a disc-shaped head, which is inserted through the top of the column to compress the foam. The head has holes drilled in it to allow water bypass, keeping the foam completely submerged during cleaning and preventing air pockets from forming. Plunging the foam creates high interstitial velocity in the foam bed, forcing entrained particles to be flushed out and creating a concentrated wastewater. This wastewater is drained through a valve located at the bottom of each column. The valve is kept open long enough to drain most of the water from the columns, keeping a layer of water above the top of the foam. The foam is then gradually allowed to expand with the plunger tool, keeping the bed submerged in the influent water until the foam core reaches its original height. In the event that the foam bed is exposed to air, bubbles are removed by closing the drain valve, filling the column with water, and plunging the foam again to force out entrained air. In a typical cleaning cycle, the roughing and finishing filters are compressed and flushed three times. The in-column cleaning process is illustrated in Figure 8.

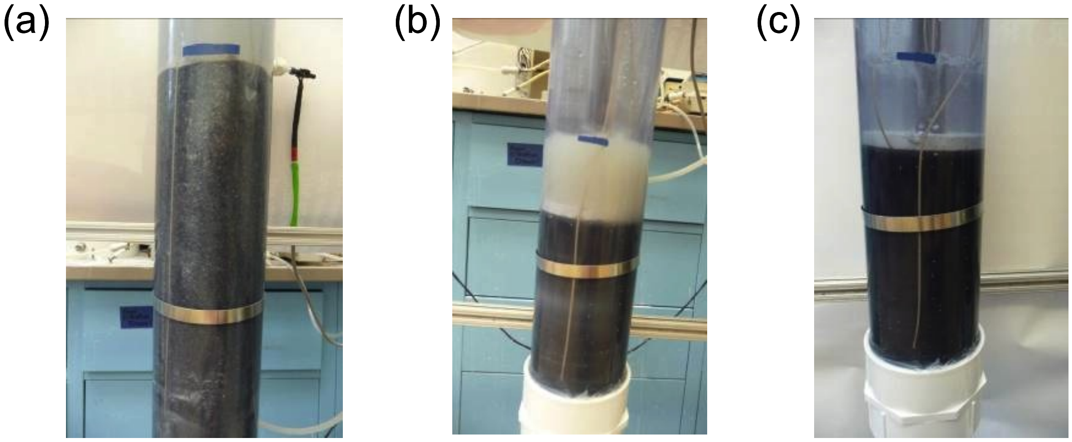

FIGURE 8. Photos of the steps in the cleaning cycle: (a) foam bed at the end of the filter cycle; (b) plunging the foam to produce concentrated wastewater, which is drained through a valve below the column; and (c) foam bed being re-filled with influent water and re-expanded

An extended performance test with influent turbidity of 450 NTU was conducted to determine the effectiveness of the in-column cleaning process to allow repeated use of the foam filters. For this test, the roughing filter was cleaned when its effluent reached 5% of the influent turbidity, or roughly 22.5 NTU. The finishing filter was not cleaned until the conclusion of the test. The roughing filter was cleaned a total of six times during this test, and after each cleaning the roughing filter effluent dropped well below 1 NTU. To simulate realistic operating conditions, the turbid influent water continued to run through the apparatus as the roughing filter was plunged and flushed. The presence of some particles in this flush water prevented the roughing filter from completely reaching pre-test capacity after cleaning, but still allowed for repeated filtration cycles to be run without removing the foam from the column. After each cleaning cycle, the effluent turbidity of the roughing filter increased, showing a gradual decrease in filter performance over time. This data suggests that the foam would still eventually reach a point where it would require a thorough cleaning and flushing with clean water.

Occasionally after a series of high-turbidity tests, filter performance decreased and effluent turbidity did not return to pre-test levels. In these cases, the roughing and finishing foam was removed from the filter columns and underwent an external cleaning cycle. This simple process consisted of running the foam under a faucet and repeatedly compressing it by hand. When the foam was reinserted into the column, it was compressed underwater to release all air bubbles. This external cycle improved filter performance, returning effluent turbidity to original low levels when the plunging method alone did not suffice. This illustrates a motive for investigating an external cleaning cycle that could be conveniently implemented in the field.

CONCLUSIONS

Polyurethane foam has been shown to be an effective medium for depth filtration of colloids from water in the presence of a coagulant. Foam can be loaded at much higher approach velocities than conventional granular media due to its higher porosity. Based on the bench-scale characterization data in this study, an approach velocity of 6 mm/s is recommended to optimize both filter area and performance. A linear relationship between filter depth and log turbidity removal was also observed. Foam is well-suited to multi-stage filtration applications: 30 ppi foam performed well as a roughing filter, and 60-90 ppi foam served as a good finishing filter.

A prototype treatment unit was developed using two foam columns in series: one 30 ppi roughing filter followed by one 90 ppi finishing filter. This unit is light, transportable, and would be readily deployed to disaster relief areas for emergency water treatment. The foam system could also presumably be used on a continuous basis for other small-scale water treatment applications. The prototype treatment unit displayed excellent turbidity removal performance, producing water well below the EPA turbidity standard of 0.3 NTU from 1000 NTU influent. A plunger-based cleaning method was also demonstrated at the prototype scale.

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