Chemosphere 74 (2009) 1396–1399

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Technical Note

Enhanced performance of crumb rubber filtration for ballast water treatment

Zhijian Tang [a], Michael A. Butkus [b], Yuefeng F. Xie [c,*]

[a] Koch Membrane Systems, Process Engineering Department, 850 Main Street, Wilmington, MA 01887, USA
[b] Department of Geography and Environmental Engineering, United States Military Academy, West Point, NY 10996, USA
[c] Environmental Engineering Programs, The Pennsylvania State University, 777 West Harrisburg Pike, Middletown, PA 17057-4898, USA

ARTICLE INFO

Article history:
Received 10 July 2008
Received in revised form 21 November 2008
Accepted 21 November 2008
Available online 31 December 2008

Keywords:
Ballast water
Crumb rubber
Filtration
Invasive species
Coagulation
Salinity

ABSTRACT

Waste-tire-derived crumb rubber was utilized as filter media to develop an efficient filter for ballast water treatment. In this study, the effects of coagulation, pressure filtration and dual-media (gravity) filtration on the performance of the crumb rubber filtration were investigated. The removal efficiencies of turbidity, phytoplankton and zooplankton, and head loss development were monitored during the filtration process. The addition of a coagulant enhanced the removal efficiencies of all targeted matter, but resulted in substantial increase of head loss. Pressure filtration increased filtration rates to 220 $m^3\ h^{-1}\ m^{-2}$ for 8-h operation and improved the zooplankton removal. Dual-media (crumb rubber/sand) gravity filtration also improved the removal efficiencies of phytoplankton and zooplankton over mono-media gravity crumb rubber filtration. However, these filtration techniques alone did not meet the criteria for removing indigenous organisms from ballast water. A combination of filtration and disinfection is suggested for future studies.

1. Introduction

Ballast water provides stability and maneuverability during a ship's voyage. Ships transfer approximately 10000 Mt of ballast water across the oceans every year. Along with the ballasting procedures, thousands of aquatic species are transported around the world each day. The introduction of unwanted alien species causes significant damage to ecological, economic and human health welfare around the globe (National Research Council, 1996; Bax et al., 2003). Mills et al. (1993) reported that over 140 alien species have been introduced to the Great Lakes of North American. Ballast water is believed to be the primary vector of unintentional transfers into the Great Lakes and other US and Canadian waters (Parsons, 2003). Ribera and Boudouresque (1995) estimated that zebra mussel alone caused damages of $5000 million from 1986 to 1995, by fouling fishing nets, boat hulls, and buoys, and blocking water intakes of power plants, water treatment plants, and other industries. The invasion of the American Atlantic coast comb jelly fish, Asian clam, and European crab, caused the collapse of fisheries in various regions (National Research Council, 1996; Bax et al., 2003). To alleviate the impacts of alien species invasion, ballast water management and treatment are essential. The newly adopted International Ballast Water Convention sets maximum concentrations of 10 viable organisms per m^3 for organisms larger than 50 μm and 10 viable organisms per mL for organisms larger than 10 μm and less than 50 μm in the minimum dimension (International Maritime Organization, 2004). The convention also sets maximum concentrations for indicator microbes: one colony forming unit (cfu) per 100 mL for toxicogenic *Vibrio cholerae* (O1 and O139), 250 cfu per 100 mL for *Escherichia coli* and 100 cfu per 100 mL for intestinal *Enterococci*.

The National Research Council (1996) evaluated a variety of approaches for removing indigenous organisms from ballast water. Among these approaches, filtration was recommended as the most promising technology. However, filtration alone may be inefficient for the removal of small size organisms (e.g., bacteria and viruses) in ballast water. Ultraviolet irradiation is effective at inactivating microorganisms (e.g., bacteria, viruses, etc.), which may not be efficiently removed by straining processes (Parsons and Harkins, 2000; Sutherland et al., 2001; Butkus et al., 2004). UV is not effective in inactivating large organisms and the presence of suspended particles (such as clay and algae) can reduce the effectiveness of UV in water (Perakis and Yang, 2003). Therefore, a combination of filtration (primary treatment) and UV or chemical disinfection (secondary treatment) might be a best available technology for treating ballast water (Perakis and Yang, 2003).

In a previous study by the authors, an innovative filtration technology, using waste-tire-made crumb rubber as filter media, was developed to remove indigenous organisms from ballast water (Tang et al., 2006a,b). Compared with conventional granular media filters crumb rubber filters weigh less, which is an important consideration for shipboard application. However, crumb rubber

* Corresponding author. Tel.: +1 717 948 6415; fax: +1 717 948 6580.
E-mail address: yxx4@psu.edu (Y.F. Xie).

0045-6535/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.chemosphere.2008.11.048

filtration alone did not achieve the target removal of invasive species proposed by the International Maritime Organization (2004) in these studies. It is well-known that filtration coupled with particle destabilization (e.g., coagulation) are effective processes for reducing turbidity, particle counts, viruses, bacteria and parasites (Nasser et al., 2002). It is also known that dual-media filtration generally has better filtration performance and reduced head loss development.

The objectives of this study were to investigate the influence of coagulation, dual-media filtration (sand/crumb rubber) and pressure filtration on the treatment of ballast water (to remove indigenous organisms and turbidity) by crumb rubber filtration. Removal of turbidity, particles, phytoplankton, and zooplankton were used to evaluate filter performance.

2. Materials and methods

2.1. Filtration design and operation

Crumb rubber filters with an internal diameter of 5 cm and a filter depth of 90 cm were constructed. The crumb rubber media used in this study had a size range of 1.2–2.0 mm. The crumb rubber media size was determined by sieve analysis using American Society for Testing and Materials (ASTM) Standard Test C136-92, Sieve Analysis of Fine and Coarse Aggregates (ASTM, 1993). The effective size was 1.2 mm. Density of the crumb rubber media was about 1130 kg m^{-3}, which is less dense than traditional filter media (sand and anthracite).

Except for pressure filtration, overflow was used to keep a constant water head. Effluent water head was measured by connecting a clear tubing to the bottom of the filters vertically and head loss was determined based on the difference between influent and effluent water head. Air scouring plus water backwash were used to clean filters following each filtration run. Filtered water was used as backwash water. Backwash was not investigated because of the wall effect of small filter columns used under this project. In a previous study with a 15 cm filter column (Hsiung, 2004), the optimized backwash water rate range was between 26 and 30 $m^3\ h^{-1}\ m^{-2}$.

The coagulation, dual-media filtration and pressure filtration studies were carried out at Gifford Pinchot State Park, Pennsylvania, USA. The average influent turbidity, phytoplankton and zooplankton in Lake Pinchot were 10.2 NTU, 4060 mL^{-1}, and 100 L^{-1}, respectively. Water pumped from Lake Pinchot was used as filter influent because lake water is a common source of ballast water.

2.2. Coagulation study

The filtration rate was set at 48.9 $m^3\ h^{-1}\ m^{-2}$ for the coagulation study. The coagulant used in this study was poly-aluminum chloride (PACl, Sternson Limited, Inc., USA) because of its high charge neutralization efficiency and low sludge production. The concentrated PACl solution was injected into the influent, and a static mixer was used to provide sufficient mixing. Jar testing and zeta-potential measurement (Zeta-Meter System 3.0+, Zeta-Meter, Inc., USA) were used to determine the optimal coagulant dosage. To investigate the impact of coagulation, two filters, one with coagulant and the other without coagulant, were operated simultaneously in each run. Various coagulant dosages were studied in several runs.

2.3. Pressure filtration

The pressure filter had the same configuration as the filters used in the coagulation study. Water head was controlled via a pump located at the influent side. The maximum influent head was 14.1 m water in this study. Three filtration rates were evaluated: 147, 195 and 220 $m^3\ h^{-1}\ m^{-2}$.

2.4. Dual-media filtration

Crumb rubber and fine sand were used as filter media for the dual-media, gravity filtration study. Various configurations were investigated: 90 cm crumb rubber only; 85 cm crumb rubber plus 5 cm sand; 75 cm crumb rubber plus 15 cm sand; and 60 cm sand only. Overflow was used to maintain a constant water head of 4 m. The filtration rate was also held constant at 24.4 $m^3\ h^{-1}\ m^{-2}$.

2.5. Monitoring parameters

Turbidity, phytoplankton, and zooplankton in the filter influent and effluent were quantified according to Standard Methods (SM) 2130, SM 2560, SM 10200 F, and SM 10200 G, respectively (APHA, 1998). Turbidity was measured by a portable turbidity meter (0.01–1000 NTU). Phytoplankton enumeration was conducted with a clear 1mL counting cell and a compound microscope (100×). Zooplankton were collected with a 50 μm plankton net, then transferred into a clear 5-mL counting cell and counted using a stereoscopic microscope (10–60×).

Generally, filters were continuously run at a controlled filtration rate. For each 8-h run, turbidity, salinity, phytoplankton, zooplankton and head loss were measured five times (at runtimes of 0.5, 2, 4, 6 and 8 h). For the coagulation study with coagulant dosage as 7 and 13.5 mg L^{-1}, the filtration study was stopped after 4 h of operation because head losses were too high and the required filtration rate could not be maintained. In this case, there were only three sampling events (0.5, 2 and 4 h).

3. Results and discussion

3.1. Coagulation study

To obtain optimal coagulant dosage, both jar testing and zeta-potential measurements were applied. The optimal coagulant dosage was determined to be about 13–14 mg L^{-1} although complete charge neutralization (zeta potential at zero) was not attained. At this dosage, final turbidity was about 3 NTU and the floc settled quickly. Jar testing also showed that a PACl dosage of about 5 mg L^{-1} reduced turbidity notably, therefore 4.5 mg L^{-1} (1/3 of the optimal dosage) was chosen as the lowest dosage studied. Half of the optimal dosage (7 mg L^{-1}) was also investigated.

The influence of coagulation on gravity filter performance is summarized in Table 1. The results shown here are the average values of several sampling events in each run ± standard deviations. Without coagulation, the removal efficiencies were about 40% for turbidity, 60% for phytoplankton and 50% for zooplankton. With coagulation, the removal efficiencies were improved to approximately 60% for turbidity, 80% for phytoplankton and 70% for zooplankton. The reasons of this enhanced filtration performance are: (1) the coagulant neutralizes the particle charge and enhances the aggregation of small particles into larger aggregates; (2) flocs formed by coagulation trap suspended matter; and (3) the sediments block or diminish the void space of the filter media, consequently increase the possibility of suspended matter being retained by the filter. Unlike the jar test results, filter performance was not substantially influenced over the range of coagulant dosages investigated (Table 1). Turbidity removal resulting from the 4.5 mg L^{-1} dosage is lower than what was indicated by jar testing and zeta-potential measurements but this is not surprising because coagulant dosages used to obtain pinpoint floc in direct

Table 1
Influence of coagulant dosages on turbidity, phytoplankton and zooplankton removal (%). The average influent turbidity, phytoplankton, and zooplankton values were 10.2 NTU, 4060 mL^{-1}, and 100 L^{-1}, respectively. Terminal head losses were: 76 cm without coagulant; 170 cm with 4.5 mg/L coagulant after 8 h of filtration; 281 cm with 7 mg/L coagulant after 4 h of filtration; and, 340 cm with 13.5 mg/L coagulant after 4 h of filtration.

Parameters		Removal efficiencies (%)					
		Turbidity		Phytoplankton		Zooplankton	
		Without coagulant	With coagulant	Without coagulant	With coagulant	Without coagulant	With coagulant
Dosage	4.5 mg L^{-1}	43 ± 3	55 ± 5	67 ± 2	81 ± 2	54 ± 9	72 ± 9
	7 mg L^{-1}	38 ± 7	67 ± 5	54 ± 0	70 ± 3	46 ± 9	69 ± 2
	13.5 mg L^{-1}	44 ± 1	61 ± 21	66 ± 2	84 ± 2	51 ± 6	66 ± 5

filtration of drinking water are often lower than dosages used in conventional treatment.

The addition of coagulant increased head loss substantially. The terminal head loss was 170 cm for filtration with coagulation (4.5 mg L^{-1}) while it was 76 cm without coagulation. Increasing the coagulant dosage also increased the head loss appreciably. The experiments for filtration with 7 and 13.5 mg L^{-1} of coagulant were stopped after 4 h because the head losses were too high to maintain the required filtration rate. More than 340 cm of head loss was developed in 4 h when the coagulant dosage was 13.5 mg L^{-1}, while head loss was only 53 cm after 4 h without coagulation. It is known that coagulation forms flocs and helps retain more suspended matter in the filter, thus reducing the filter void space and increasing the head loss.

3.2. Pressure filtration

Pressure filtration was studied at filtration rates of 147, 195 and 220 $m^3\ h^{-1}\ m^{-2}$. The removal efficiencies of target matter (turbidity, zooplankton, and phytoplankton) were monitored and are presented in Table 2.

Pressure filtration removed about 16% turbidity, 60% phytoplankton and more than 90% zooplankton. The removal efficiencies for gravity filters at a filtration rate of 24.4 $m^3\ h^{-1}\ m^{-2}$ were about 19% for turbidity, 58% for phytoplankton and zooplankton. There was a substantial increase in zooplankton removal efficiency by pressure filtration, while no substantial changes were observed for the removal of turbidity and phytoplankton. The increase in zooplankton removal might be due to the crumb rubber compression, which reduces the void space in the filter (particularly at high filtration rate) and enhances the removal efficiency by straining. However, removal of turbidity and phytoplankton was not improved. It should be noted that in our study, the targeted phytoplankton were in the size range of 10–50 μm while the targeted zooplankton were larger than 50 μm (minimum dimension). However, the results from the coagulation study showed that phytoplankton removal is the same as or even better than zooplankton removal when the filtration rate was 73.3 $m^3\ h^{-1}\ m^{-2}$ or less. It is presumed that viable mobile zooplankton can penetrate the filter layer by themselves under low filtration rate conditions. And, under the high filtration rate condition, the mobility and penetration of zooplankton is limited and removal efficiency is improved. However, further study is needed to verify this hypothesis.

In the pressure filtration study, the filtration rate was kept constant by adjusting the influent water pressure. The required water pressure in the influent increased notably after 6 h of run time for the filtration rates of 195 and 220 $m^3\ h^{-1}\ m^{-2}$. For the filtration rates of 147 and 195 $m^3\ h^{-1}\ m^{-2}$, the filter could be run for 8 h continuously. For the filtration rate of 220 $m^3\ h^{-1}\ m^{-2}$, the filter was stopped after 7 h of operation because the required filtration rate could not be maintained at the maximum influent head of 14.1 m water.

3.3. Dual-media filtration

The dual-media filtration study was conducted at a filtration rate of 24.4 $m^3\ h^{-1}\ m^{-2}$. The results from this study are summarized in Table 3. Compared to the crumb rubber mono-media filter, removal efficiencies of all targeted matter by dual-media filters were notably enhanced. Crumb rubber/sand dual-media filters removed more than 70% phytoplankton and 90% zooplankton in various configurations. The removal of turbidity was also enhanced.

Because crumb rubber has a lower specific weight than sand, the larger size crumb rubber settles as the top layer of filter media and the small size sand will form the bottom layer after backwash. This stratification results in an ideal filter configuration in which large suspended matter can be removed at the top layer and small matter can be removed at the bottom layer. The results also indicate that a filter with just a 5 cm sand layer plus a crumb rubber layer can provide the same removal as the filters with deeper sand layers. The use of 5 cm sand layer plus crumb rubber layer will not substantially increase filter weight.

The head losses during dual-media filtration were also monitored and compared. The head loss increases substantially with increasing sand layer depth. For the crumb rubber only filter, the head loss was 20 cm after an 8-h run, while head loss was 112 cm for the filter with 5 cm of sand and 85 cm crumb rubber.

Table 2
Removal efficiencies (%) of targetted matter by pressure filtration. The average influent turbidity, phytoplankton, and zooplankton values were 5.3 NTU, 1467 mL^{-1}, and 167 L^{-1}, respectively. The required head to maintain the design filtration rate after eight hour filtration were 0.2 m of water for 24 $m^3\ h^{-1}\ m^{-2}$, 5.6 m of water for 147 $m^3\ h^{-1}\ m^{-2}$, and, 7.0 m of water for 195 $m^3\ h^{-1}\ m^{-2}$. A filtration rate of 220 $m^3\ h^{-1}\ m^{-2}$ required a head of 14.1 m of water for 7 h of filtration.

Filtration rate ($m^3\ h^{-1}\ m^{-2}$)	Removal efficiencies (%)		
	Turbidity	Phytoplankton	Zooplankton
24	19 ± 6	58 ± 4	58 ± 9
147	16 ± 3	60 ± 6	92 ± 3
195	16 ± 1	60 ± 4	90 ± 2
220	17 ± 2	57 ± 10	92 ± 6

Table 3
Removal efficiencies (%) of dual-media filters for a filtration rate of 24.4 $m^3\ h^{-1}\ m^{-2}$. The average influent turbidity, phytoplankton, and zooplankton values were 5.4 NTU, 1392 mL^{-1}, and 22 L^{-1}, respectively. Terminal head losses were: 20 cm of water for 90 cm crumb rubber following eight hours of filtration; 112 cm of water for 85 cm crumb rubber + 5 cm sand following 8 h of filtration; 234 cm for 75 cm crumb rubber + 15 cm sand following 6 h of filtration; and, 361 cm for 60 cm sand following 2 h of filtration.

Layer composition	Removal efficiencies (%)		
Crumb rubber + sand	Turbidity	Phytoplankton	Zooplankton
90 cm crumb rubber only	19 ± 6	58 ± 4	58 ± 9
85 cm crumb rubber + 5 cm sand	28 ± 6	71 ± 2	93 ± 2
75 cm crumb rubber + 15 cm sand	36 ± 3	72 ± 7	92 ± 6
60 cm sand only	27 ± 1	71 ± 1	96 ± 4

The 5 cm sand filter could be run for 8 h at a filtration rate of 24.4 $m^3 h^{-1} m^{-2}$. For the filter with 15 cm sand, the head loss was 234 cm after 6 h of operation, and the test was stopped because of high head losses. The 0.6 m sand only filter developed head loss so fast that the required filtration rate of 24.4 $m^3 h^{-1} m^{-2}$ lasted for only 2 h.

4. Conclusions

The addition of coagulant improved the removal of targeted matter (turbidity, phytoplankton, and zooplankton). In the coagulant dose range of 4.5–13.5 mg L^{-1}, targeted matter removal efficiencies did not change appreciably with dosage. The addition of coagulant increased head loss remarkably.

Under a water head of 14.1 m water, filtration rates as high as 220 $m^3 h^{-1} m^{-2}$ for an 8-h filter run were achieved, resulting in more than 90% zooplankton removal. It is found that high filtration rate benefited zooplankton removal.

Crumb rubber/sand dual-media enhanced filtration performance: more than 70% phytoplankton and 90% zooplankton were removed. With an influent water head at 4 m, a 5 cm sand plus 85 cm crumb rubber filter could be run for more than 8 h with a filtration rate of 24.4 $m^3 h^{-1} m^{-2}$.

This study indicated the dual-media pressure filter could enhance the performance of crumb rubber filtration notably, with limited increase in filter head loss and filter weight. Therefore, a comprehensive investigation of the crumb rubber/sand dual-media pressure filter for ballast water treatment is necessary to find a potential technology for onboard ballast water treatment. A combination of the crumb rubber filtration and chemical/physical disinfection (e.g., UV radiation) for ballast water treatment should be investigated in future studies because the filtered water did not meet the ballast water treatment criteria.

Acknowledgements

This study was supported by the United States National Oceanic and Atmospheric Administration (NOAA) under a Project NA04OAR4170151. During the study, Zhijian Tang was a postdoctoral scholar at the Pennsylvania State University. The field study was done with the assistance of William Rosevear, Manager of Gifford Pinchot State Park in Pennsylvania.

References

APHA, 1998. Standard Methods for the Examination of Water and Wastewater, 20th ed. American Public Health Association, Washington, DC.

American Society for Testing and Materials, 1993. Concrete and aggregates. 1993 Annual Book of ASTM Standards, vol. 0402. Philadelphia.

Bax, N., Williamson, A., Aguero, M., Gonzalez, E., Geeves, W., 2003. Marine invasive alien species: a threat to global biodiversity. Mar. Policy 27, 313–323.

Butkus, M.A., Labare, M.P., Starke, J.A., Moon, K., Talbot, M., 2004. Use of aqueous silver to enhance the inactivation of coliphage MS-2 with UV disinfection. Appl. Environ. Microb. 70, 2848–2853.

Hsiung, S.-Y., 2004. Filtration Using a Crumb Rubber Filter Medium: Preliminary Studies Using Secondary Wastewater Effluent as Feed. M.S. Thesis, The Pennsylvania State University, University Park, Pennsylvania, USA.

International Maritime Organization, 2004. International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004. In: International Conference on Ballast Water Management for Ships, London.

Mills, E.L., Leach, J.H., Carlton, J.T., Secor, C.L., 1993. Exotic species in the Great Lakes: a history of biotic crises and anthropogenic introductions. J. Great Lakes Res. 19, 1–54.

Nasser, A., Huberman, Z., Dean, L., Bonner, F., Adin, A., 2002. Coagulation as a pretreatment of SFBW for membrane filtration. Water Sci. Technol.: Water Supply 2, 301–306.

National Research Council (NRC), 1996. Stemming the Tide: Controlling Introductions of Nonindigenous Species by Ships' Ballast Water. National Academy Press, Washington, DC.

Parsons, M.G., Harkins, R.W., 2000. The great lakes ballast technology demonstration project filtration mechanical test program. Mar. Technol. 37, 129–140.

Parsons, M.G., 2003. Consideration in the design of the primary treatment for ballast systems. Mar. Technol. 40, 49–60.

Perakis, A.N., Yang, Z.Y., 2003. Options for nonindigenous species control and their economic impact on the Great Lakes and St. Lawrence seaway: a survey. Mar. Technol. 40, 34–41.

Ribera, M.A., Boudouresque, C.F., 1995. Introduced marine plants, with special reference to macroalgae: mechanisms and impact. In: Round, F.E., Chapman, D.J. (Eds.), Progress in Phycological Research, vol. 11. Biopress Ltd. Publ, Bristol, pp. 187–268.

Sutherland, T., Levings, C., Petersen, S., Hesse, W., 2001. The influence of cyclonic separation and UV treatment on the mortality of marine plankton. In: The 1st International Ballast Water Treatment R&D Symposium Proceedings. IMO, London.

Tang, Z., Butkus, M.A., Xie, Y.F., 2006a. Crumb rubber filtration: a potential technology for ballast water treatment. Mar. Environ. Res. 61, 410–423.

Tang, Z., Butkus, M.A., Xie, Y.F., 2006b. The effects of various factors on ballast water treatment using crumb rubber filtration: pilot study and statistic analysis. Environ. Eng. Sci. 23, 561–569.