Chemosphere 117 (2014) 360–366

Contents lists available at ScienceDirect

Chemosphere

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

Effect of temperature on the performance of laboratory-scale phosphorus-removing filter beds in on-site wastewater treatment

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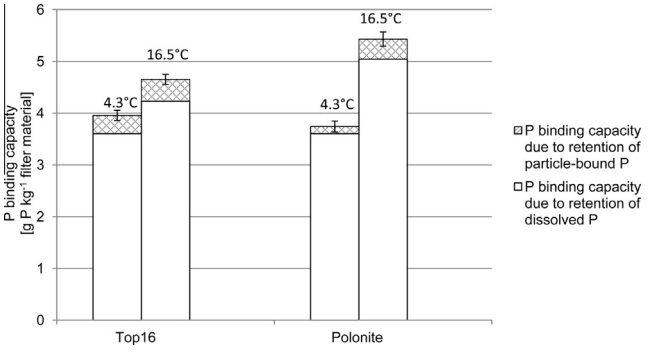
HIGHLIGHTS

- Phosphorus-removing filter materials for onsite wastewater treatment were studied.
- Two commercial filter materials were tested at 4.3 and 16.5 °C.
- P binding capacity of both materials increased with increasing temperature.
- More particulate organic carbon was retained at the higher temperature.
- The effluent pH and reduction in DOC levels were not affected by temperature.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 3 April 2014
Received in revised form 16 July 2014
Accepted 17 July 2014

Handling Editor: O. Hao

Keywords:
Polonite
Top16
Constructed wetlands
Reactive filter
Secondary wastewater
Small-scale

ABSTRACT

P-sorbing filter beds appear to be viable options for treating wastewater to reduce P discharges and recover this non-renewable resource. However, greater knowledge of filters' responses to temperature variations is required to assess their likely performance in full-scale applications and facilitate the transfer of laboratory results to the field. Thus, in the present study two filter materials (Top16 and Polonite) were characterized physicochemically and effects of temperature on their performance were investigated under controlled laboratory conditions. Using a 2^2 factorial design and secondary wastewater eight filter columns were tested at temperatures of 4.3 °C and 16.5 °C. Temperature significantly ($\alpha = 0.05$) and strongly affected the P binding capacity of both materials, as it was 1.2- and 1.5-fold higher at 16.5 °C than at 4.3 °C for Top16 and Polonite, respectively. This is probably due to the enhanced precipitation of calcium phosphates at higher temperature. Observed reductions in total organic carbon content in the wastewater were also positively correlated with temperature, while the pH and reduction of dissolved organic carbon remained unaffected. The physicochemical analyses indicated that several calcium phases dissolved from the filter materials, primarily gypsum and bassanite from Top16 and Portlandite from Polonite. No clear evidence of any crystalline calcium phosphates was observed in the used materials. The results clearly show that temperature strongly influences the retention of P in filters and its effects should be carefully considered before using candidate filters in full-scale applications.

1. Introduction

The removal of P in onsite wastewater treatment facilities can be enhanced by adding P-sorbing materials to constructed wetlands or retrofitting P-sorbing filters into existing facilities. A number of potential filter materials have been investigated (Johansson

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http://dx.doi.org/10.1016/j.chemosphere.2014.07.069
0045-6535/

Westholm, 2006; Vohla et al., 2011), but many only at laboratory scale. The field performance and lifetime of these filter materials have proven dependency on several variables, including properties of the influent wastewater, the flow regime and both the age and size of the filter. The P binding capacity of these materials, as determined in laboratory scale investigations, is also affected by diverse factors, including the influent P concentration (Herrmann et al., 2014), loading rate (Herrmann et al., 2013, 2014) and influent type (Herrmann et al., 2013). Thus, the performance of filter materials in field conditions often differs substantially from predictions based on laboratory observations. For example, Renman and Renman (2010) found that filters containing Polonite removed less P when placed outdoors than when placed indoors, although the loading rate outside was lower. Besides the factors listed above, the temperature could also have influenced these results. In accordance with this hypothesis, Agyei et al. (2002) found that increases in temperature enhanced P binding to fly ash, slag and Portland cement. In addition, phosphate adsorption to soil has been shown to be exothermic and thus temperature-dependent (Barrow and Shaw, 1975). Furthermore, in many filter materials dissolved P is precipitated by calcium ions released by dissolving minerals, e.g. wollastonite, which has temperature-dependent dissolution rates (Sverdrup, 1990). The precipitation of calcium phosphates such as hydroxylapatite (HAP) is also affected by temperature because their solubility products are temperature-dependent (Appelo and Postma, 1993). Therefore, the saturation index of HAP increases linearly with temperatures between 5 and 30 °C, as confirmed by thermodynamic calculations (Song et al., 2002). In addition, temperature controls crystal growth (Wang and Nancollas, 2008) and is thus important for the formation of HAP and other types of calcium phosphate crystals. Temperature could also affect the performance of P filters indirectly by influencing growth rates of microbes in them.

As laboratory filter tests are commonly performed at room temperature, temperature effects may explain at least some of the deviations between laboratory results and full-scale performance. Variations in temperature may also contribute to unpredictable fluctuations in the performance of filter materials in field applications. However, effects of temperature on the P-binding capacity of P-sorbing materials have not been previously investigated under controlled conditions. Thus, in the present study two filter materials were physicochemically characterized and effects of temperature on their performance when treating secondary wastewater under controlled conditions in the laboratory were investigated.

2. Material and methods

2.1. Materials

The two filter materials investigated in this study were Polonite (from Bioptech AB, Sweden) and Top16 (from Envitop Oy, Finland). Polonite has been studied previously (e.g. Gustafsson et al., 2008). Top16 was manufactured from ferrous sulfate monohydrate and burnt lime which were granulated in a rotating mixing device. Due to exothermic reactions occurring during the mixing process, temperatures of ca. 80 °C were reached. Samples of the two materials (which came in ca. 30 kg bags) were formed by fractional shoveling and further divided using a riffle splitter to obtain representative sub-samples of appropriate sizes for the analyses and experiment. The sub-samples were then dried overnight at 105 °C and brought to room temperature in an exsiccator.

2.2. Material characterization

To characterize the materials, the following parameters were determined: total solids (TS), loss on ignition (LOI), total content of elements, mineral composition, PSD, bulk density and porosity.

The elemental analysis was performed using inductively coupled plasma sector field mass spectrometry (ICP-SFMS). X-ray powder diffraction (XRPD) analyses were performed on fresh samples of both materials and used filter material (one sample of each material taken from the filter column with the highest P binding capacity). Samples were wet ground and spray-dried to produce random powders, then their XRPD patterns were recorded from 2 to 75° 2θ using Cobalt Kα radiation.

The particle size distribution of each material was determined according to the Swedish standard (Swedish Standards Institute, 1992) using ca. 1.5 kg sub-samples and sieves with suitable mesh sizes (0.5–20 mm for Top16; 0.5–8 mm sieves for Polonite).

The bulk density of Top16 and Polonite was determined using 4.1 kg and 4.6 kg samples, respectively. Both samples were split into 6 sub-samples using a riffle splitter. After drying and cooling, each sub-sample was placed in a measuring cylinder and its weight and volume were recorded.

The porosity of the materials was determined by placing 500 mL water and 500 mL of a bulk sample of material (from representative portions of Top 16 and Polonite weighing 2.7 and 3 kg, respectively) into a measuring cylinder and recording the total volume. The procedure was repeated 6 times with Top16 samples and 7 times with Polonite samples.

2.3. Filter experiment

2.3.1. Experimental design and set-up

The effect of temperature on the P binding capacity of the two materials was investigated in a filter column experiment (Fig. 1) using a 2^2 full factorial design (Montgomery, 2009) with replicates ($n = 2$), as follows. A ca. 3 cm thick layer of glass beads was placed at the bottom of each of eight acrylic columns (diameter 7.4 cm), followed by 200 g of Top16 in four of the columns and 200 g of Polonite in the other four. Two with each material were placed in a cooling container at a low temperature (4.3 ± 0.4 °C, resembling winter conditions for full scale filters) while the other four were kept in at room temperature (16.5 ± 2.9 °C, resembling conditions during laboratory tests). Wastewater (described below) was then continuously fed through them (via a peristaltic pump) in up-flow mode at an average loading rate of 1.47 L d^{-1}, corresponding to a surface load of 342 L m^2 d^{-1} and residence time of 2.5 H (Top16) and 2.3 H (Polonite). This loading rate corresponds to typical loading rates of full-scale filters with 900 mm diameter for two persons with an average water consumption of 109 L d^{-1}. During the tests, a funnel filled with glass beads was put on top of the columns to ensure a smooth outflow, the effluent was collected in plastic containers and its weight was recorded. The experiments started on 2013-03-05 and were run for a duration of 111 d until 2013-06-24.

2.3.2. Influent

The wastewater used as an influent was collected twice weekly from Ängesbyn wastewater treatment plant, which is located ca. 30 km north of Luleå, Sweden. At the plant, which serves 300 person-equivalents (pe), the incoming water is screened and then treated by an activated-sludge process. The wastewater used for the experiment was sampled from the surface of the sedimentation basin. Phosphate solution (prepared with K_2HPO_4 and distilled water) was added to obtain the target P concentration of 12 mg P L^{-1}. The following influent parameters were measured (Table 1): total P and dissolved P (total P in samples passed through a 0.45 μm filter) contents; total organic carbon (TOC) and dissolved organic carbon (DOC) contents, the latter measured as TOC in samples passed through a 0.45 μm filter; BOD_7; pH; redox potential; and total suspended solids (TSS) content. The temperatures of the influents (Table 1) were recorded half-hourly during the experiment.