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Technical Note

Long-term phosphate removal by the calcium-silicate material Polonite in wastewater filtration systems

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ABSTRACT

The mineral-based filter material Polonite was tested for its PO_4 removal capacity in column and full-scale systems using synthetic and domestic wastewater. Three long-term experiments (67, 68 and 92 wk), operated under different hydrological conditions, were compared. The best PO_4 removal capacity (97%) was observed in an intermittent saturated column fed with a synthetic solution (530 L m^{-2} d^{-1}) without organic matter during 68 wk. An unsaturated column system using municipal wastewater (76.7 L m^{-2} d^{-1}) showed no tendency for PO_4 breakthrough and effluent PO_4 concentration was still low (0.2 mg L^{-1}) after 67 wk. For a compact bed filter containing 560 kg of Polonite and fed with 70 m^3 of wastewater from a single house, the average PO_4 removal was 89% after 92 wk of operation. The column experiments revealed that a design volume of 1–2 kg of material of a particle size of 2–5 mm was required amount for treating 1 m^3 of wastewater in on-site systems operating at target 90% P mass removal. Poor pre-treatment of the wastewater was suggested to reduce the phosphate removal capacity of Polonite in the bed filter trial, where 8 kg were required per m^3. To measure pH of the treated effluent water proved not to be a simple tool for determining when the filter material is exhausted and should be replaced.

1. Introduction

The lack of proper wastewater treatment in rural areas contributes greatly to the pollution of surface waters and groundwater. Technical solutions suitable for treating small wastewater flows from single houses or villages are available (Crites and Tchobanoglous, 1998; Jantrania and Gross, 2006). These include e.g. more passive systems such as soil infiltration, or advanced systems such as small package treatment plants. Ecologically based, on-site treatment systems such as constructed wetlands have also been employed to treat wastewater in a number of studies (cf. Vymazal, 2005). Whereas conventional, large-scale treatment systems are technically constructed in the same way all over the world, small-scale systems are available in a large number of types. The effect of this differentiation is a corresponding variation in treatment results, mainly because of limited management and control of the small systems. In particular, the removal of phosphorus by these systems has been shown to be inadequate when compared against statutory effluent criteria for treated wastewater. In the case of package plants, it is necessary to use reliable dosing equipment and professional personnel for service, maintenance and technical support in order to achieve long-term P removal (Hellström and Jonsson, 2006).

Phosphorus removal from wastewater is of particular concern as it is the limiting nutrient in most fresh, inland surface water systems (Schindler, 1977). However, many types of small-scale systems have demonstrated poor P removal. The sands and gravels used in most constructed wetlands have a negligible long-term capacity for P removal (Vymazal et al., 1998). This has led researchers to look for more efficient materials for use in wetlands. A great number of organic and inorganic materials have recently been tested in laboratory and field-scale trials (Drizo et al., 2006; Johansson Westholm, 2006; Ádám et al., 2007; Kaasik et al., 2008; Leader et al., 2008; Dobbie et al., 2009). Mineral-based materials with a reactive character in contact with wastewater have demonstrated good P removal performance depending on various removal mechanisms (e.g. Gustafsson et al., 2008; Eveborn et al., 2009). Among these, a commercial product named Polonite and manufactured from the bedrock opoka, has emerged as a promising material for use in full-scale treatment systems. Powdered and high-thermal treated opoka (Polonite) has a maximum PO_4 sorption capacity of about 120 g kg^{-1} in contact with a synthetic P-solution (Brogowski and Renman, 2004). However, powder of any material cannot be included in treatment systems based on filtration as the fine material causes clogging and hydraulic failure. Hence an optimal particle size can be 1–2 mm for achieving a

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desirable removal and hydraulic capacity simultaneously (cf. Yao et al., 1971).

A compact filter system using the filter media Filtralite P with a particle size of 0–4 mm has been developed in Norway (Heistad et al., 2006). This system has proved to be robust when applied on-site in rural areas, with stable P removal over many years. However, the filter material used showed an overall P-sorption capacity of 52 mg P kg^{-1} applied in a full-scale system, which was 85×10^3 times lower than the findings from a laboratory small-scale system using a synthetic P-solution (Ádám et al., 2006). This large discrepancy raises many questions, particularly concerning the estimation of P-retention lifetime of filter materials. The present paper analyses a similar compact filter system developed in Sweden, which uses Polonite as the reactive filter material for P removal, and its design allows for easy replacement of material and reuse of the spent material in agriculture. In contrast to the chemical products used for precipitation of P in wastewater, Polonite is more valuable as a multi-component fertilizer or amendment in soils (Hylander and Simán, 2001; Hylander et al., 2006; Cucarella et al., 2008; Cucarella et al., 2009). Reactive bed filter (RBF) systems are designed for simple operation and minimal management, which renders them useful for treatment of wastewater from single houses or small populations (Renman, 2008).

The overall aim of the present study was to examine the long-term PO_4 removal capacity of Polonite in pilot-scale columns using artificial and municipal wastewater and a compact bed filter treating wastewater from one household. Other parameters and purification issues were studied in these experiments, but in the present paper, phosphorus was selected for closer analysis. Phosphorus is a critical nutrient input in agriculture and its global reserves are being rapidly depleted (Cordell et al., 2009). The use of Polonite in wastewater filtration systems gives opportunities for recovering phosphorus. Specific objectives were to: (1) estimate the longevity of Polonite in relation to effluent phosphate standards and propose the design volume of material for full-scale treatment systems; and (2) assess whether the pH of the treated wastewater could be used as a simple indicator for P breakthrough and P saturation; and (3) determine the content of P accumulated in spent filter media for recycling.

2. Experimental methods

The effect of different scales and flow regimes on PO_4 removal by Polonite (particle size of 2–5.6 mm) was evaluated in three different experiments. Experiments A and B were performed in indoor columns at room temperature (20 °C), while experiment C was a full-scale operating filter well. The filter well was an underground construction with an insulated lid visible on the surface and hence the filter was exposed to varying temperature (4–20 °C).

2.1. Polonite – the reactive material used

Polonite is produced in Poland from the sedimentary rock opoka after thermal treatment to 900 °C, crushing and sieving into appropriate fractions. Opoka is a Polish-Russian term with no English equivalent. The rock, of Cretaceous age, is calcareous, but hardened as a result of the presence of organic silica (Brogowski and Renman, 2004). After heating, $CaCO_3$ is transformed to the more reactive CaO, a procedure aimed at enhancing the P removal capacity of the material. Polonite is usually produced in the 2–5.6 mm fraction, and thus has very good hydraulic properties (800 m d^{-1}). This fraction was used here in all three experiments. However a tail of fine particles less than 1 mm can sometimes be found in the manufactured material, thereby decreasing the hydraulic conductivity. Brogowski and Renman (2004) and Gustafsson et al. (2008) described the elemental composition of Polonite.

2.2. Column fed with synthetic solution (A)

One column filled with Polonite was used in a long-term laboratory experiment. Other potential filter materials for P and N removal were also involved in this experiment and are dealt with in other publications (Gustafsson et al., 2008). The column was constructed of a PVC tube of 60 cm length and 10 cm inner diameter. The filter bed was 50 cm and the Polonite used was sieved to remove particles less than 2 mm. To minimise any effects of chemical clogging, i.e. the formation of $CaCO_3$, the composition of the Polonite was modified by the addition of 10% (w/w) *Sphagnum* peat. The starting pH of the mixture was 11.8.

A synthetic solution containing 5 mg L^{-1} PO_4–P and 30 mg L^{-1} NH_4–N was prepared by adding KH_2PO_4 and NH_4Cl to tap water. The solution was stored in two containers (200 L each) and pumped automatically to the top of the column three times per day (times 08.00, 13.00, 17.00) throughout the experimental period of 68 wk (71 wk including breaks for technical maintenance). In experiment A, each loading of solution was proportional to the pore volume of Polonite in the column, i.e. 1.4 L and the column substrate was constantly saturated. Data on loading rates and number of pore volumes treated in all experiments are shown in Table 1.

2.3. Columns fed with municipal wastewater (B)

Duplicate columns (height 50 cm, diameter 30 cm) containing pure Polonite were installed and fed with wastewater at the Loudden wastewater treatment plant in Stockholm as part of a long-term experiment involving six filter materials. Details of the entire column experiment can be found in Renman et al. (2004) and Hylander et al. (2006). The raw wastewater was pre-treated by sedimentation and filtration before discharge to the columns at an average volume of 0.45 L every second hour for a period of 67 wk. The concentration of PO_4 in the influent wastewater was 4.1 ± 0.9 mg L^{-1} and the starting pH of the filter material was 12.5.

2.4. Bed filter fed with wastewater from a single household (C)

The operation of a RBF plant installed for treatment of domestic wastewater from a single household in the village Viksta, adjacent to the city of Uppsala, Sweden, was studied. The treatment system consists of a sedimentation tank (3 m^3) from which the wastewater flows to a pump chamber. A timer, overrun by a float switch, controls the pump that doses portions of wastewater in relation to its production to the Polonite bed filter. This is housed in a circular container with an inner diameter of 1.43 m and depth of 0.75 m, filled with 560 kg of Polonite (volume 800 L) to a depth of 0.6 m. The container can be removed from the filter well for exchange and recycling of Polonite. The experiment started with pumping

Table 1
Hydrological conditions for the three experiments.

Experiment/flow system	A saturated	B[a] unsaturated	C intermittent saturated
Average loading rate (L m^{-2} d^{-1})	530	76.7	60.2
Hydraulic conductivity (m d^{-1})	226	800	550
Pore volumes treated (number)	1410	151	216
Hydraulic residence time (h)	4–15	–	1–72

[a] Average value for the two columns used.