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Kinetic studies on removing phosphate from synthetic solution and river water by reactive material in a form of suspended reactive filters

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ABSTRACT

The research investigates the mechanisms and the efficiency of sorption process based on the pseudo-first and pseudo-second kinetic order models describing phosphate removal by reactive material (RM) Polonite® implemented in the form of suspended reactive filters. An estimation of the optimal mass to volume ratio for practical use of RM in field conditions is an additional aim of this study. Two liquids were used (synthetic solution [SS] and river water [RW]) with three mass of RM to liquid volume ratios: 1 g:1 L, 5 g:1 L and 10 g:1 L. The results obtained after 30 d, better correspond to the pseudo-second kinetic order model which provides that chemisorption is the main sorption mechanism of phosphate removal. Depending on predicted results the recommended mass to volume ratio for prospective use is 1–5 g:1 L. The ratio 1 g:1 L promotes long-lasting sorption by RM and gives high unit sorption of 3.147 and 1.875 mg·g^{-1} for SS and RW experiments, respectively. The ratio of 5 g:1 L favors fast phosphate removal: 94% and 64% concentration removal for SS and RW along 4 d, respectively. The studies showed that irrespective of RM mass, phosphate removal efficiency from RW was lower of around 40% comparing with SS.

Keywords: Box experiment; Polonite®; Pseudo-first-order kinetic model; Pseudo-second-order kinetic model; Sorption; Reactive material

1. Introduction

The surplus of phosphorus (P) is a major cause of eutrophication of inland waters, which nowadays is a global environmental problem [1,2]. For this reason, it is important to reduce the P loads to surface water. The most P-endangered places in rural areas are drainage ditches, small streams and mid-field ponds which are the main receivers of pollutants runoff from these areas. The surplus of P in water leads not only to eutrophication process but also for future limitation of perspective water usage, for example, drinking (bad taste and smell, high costs of treatment), fish farm, and recreation. By small water bodies, P can be transported for long distance, and as a cumulated load, pollutes main rivers, seas, and oceans. Thus why, it is very important to reduce the amount of P in water at the source of its influent. One of the solutions to decrease concentration of water contamination is to use specially dedicated reactive materials [3–10].

Sorption processes are proved to be an effective method for the treatment of polluted liquids [11–13]. A calcined opoka rock (manufactured as a Polonite®) has been successfully used as an RM for reducing P from green roofs effluents [14], dedicated material for reactive filters at swimming ponds [15], wastewater treatment [7], a ditch filter to remove P from non-point sources [16]. Additionally, the P saturated RM after wastewater treatment was successfully used as a fertilizer [17]. The most popular and world-wide used kinetic models are the pseudo-first and pseudo-second-order kinetic models which explain the solid and liquid adsorption processes [11,12]. The main aim of chemical kinetics is to predict and explain the rate of the reaction and also the factors affecting the reaction rate [11]. The knowledge of the kinetic parameters

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is important at the moment of filtration system design. The optimal residence time fixing and the filter dimensions are controlled by the system's kinetics. The kinetics reaction models provide information about physical or chemical characteristics of the sorption with RMs and also on the system conditions, for example, solution concentration [11,12].

Novelty of this study is the application of RM in the form of filters suspended in the treated water. Suspended reactive filters (SRFs) are designed for P removal from small water reservoirs, which are stagnant [5] as well as small streams and agricultural ditches [18]. The system consists of curtains with bags filled with RM, and suspended in the treatment water. Application of RM in the form of SRFs enables direct contact of material with the water. If applied to small agriculture reservoirs, the stagnant water conditions are adequate to promote long contact time to obtain sufficient sorption of P. SRFs are easy to install and de-install in field conditions. They can be placed in endangered area of storage or concentration of nutrients such as dairy farms [19], after mineral fertilization or manure application [20] or in times of intensified P runoff during pre-growing or early growing season, and storm water runoff [21]. The others main advantages of SRFs are lack of interference of banks structure, no need of changing the shape of the banks and bottom, no need to use the by-pass to direct the water flow, easy installation without using heavy equipment, easy replacement of saturated RM, the possibility of seasonal use in periods of increased input of pollutants, the adjustable length of the string enables customization of the depth and level of water and construction made of unattractive materials preventing stealing. The SRFs system is patented in Poland (P.403571).

The aim of this study is to: (i) identify the mechanisms and efficiency of sorption process based on the pseudo-first and pseudo-second-order kinetic models of RM Polonite® implemented in the form of SRFs, (ii) estimate optimal mass to volume ratio for prospective use of RM in field conditions.

2. Material and methods

2.1. Characteristic of the reactive material

The material used in this study is opoka, a calcium silicate sedimentary rock, heated at a temperature of 900°C. Manufactured opoka is named Polonite® and produced by Ecofiltration, Sweden (previous name Bioptech). The physical properties of material was determined in accordance with the following standards: particle size PN EN 933-1:2012 [22], bulk density PN EN 1097-3:2000 [23] and porosity PN-EN 1936:2010 [24]. The chemical and mineral composition was indicated by XRF (spectrometer PW 2400, Philips, Holland) and XRD (X-ray diffractometer PW 3020, Philips). Physical properties, chemical and mineral composition of Polonite® used in the study are set up in Table 1.

2.2. Suspended reactive filter experiment

The experiment was performed indoor, at room temperature (~20°C). Two rows of three plastic boxes each (total six boxes) (Fig. 1) were filled with the volume of 10 L of synthetic P solution (SS) or river water (RW). The volume of each sample was 40 mL and the initial volume was recalculated of this volume. Three variants of RM mass to volume ratio were used: 1 g:1 L, 5 g:1 L and 10 g:1 L. RM of different weights (10, 50 and 100 g) was wrapped in a filter bag made of polyester textile with a 1 mm mesh, then put into boxes, and suspended. Phosphate solution was prepared by dissolving KH_2PO_4. Surface water originated from a small highly polluted low-land Cetynia river (22°26′E; 52°44′N) in Poland, which is a receiver of wastewater from municipal treatment plant in Sokołów Podlaski and runoff from agriculture catchment. Boxes were covered to limit evaporation and penetration of light. The parameters characterizing the initial conditions of experiment are set in Table 2. The experiment lasted 30 d, and during this time 15 samples from each box were collected to observe a behavior of phosphates and pH in the contact with RM. Samples were filtered through a 0.45 μm filter and P-PO_4 concentration was analyzed by flow injection analysis (FIAStar 5000). Before filtration, pH was measured by a Voltcraft PH-212 meter.

Table 1
Chemical and mineral composition with physical properties of Polonite®

Chemical composition (%)	
SiO_2	55.11
CaO	23.86
Al_2O_3	5.65
Fe_2O_3	2.10
Mineral composition (%)	
Calcite	40.0
Silica	38.0
Quartz	22.0
Other characteristics	
Particle size (mm)	2.0–5.0
Bulk density (g cm^{-3})	0.78
Porosity (%)	38.0
P sorption (g kg^{-1})	
Maximal observed in the study	3.147
Estimated from Langmuir isotherm	96.58

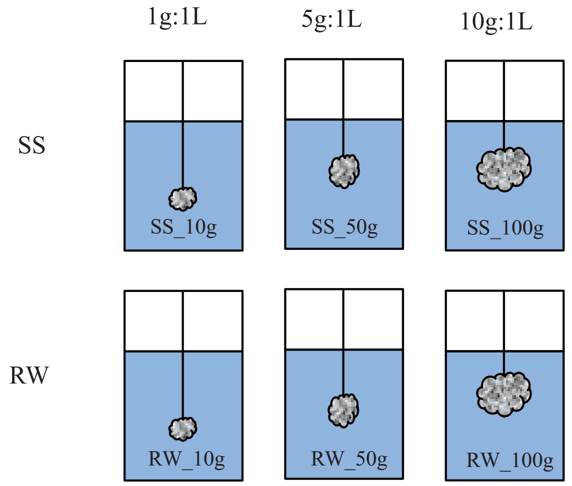

Fig. 1 Set up of the SRFs box experiment with different mass to volume ratios.

Table 2
Initial characteristic of liquids used in the SRF experiments. In case of concentration min-max values are presented

Parameter	Synthetic P solution (SS)	River water (RW)
P-PO$_4$ (mg·L^{-1})	3.483–3.839	2.923–2.959
NO$_3$ (mg·L^{-1})	–	58.0
NO$_2$ (mg·L^{-1})	–	0.14
NH$_4$ (mg·L^{-1})	–	0.80
pH	6.44	7.78
EC (mS·cm^{-1})	0.003	1.3
BOD$_5$ (mgO$_2$ L^{-1})	–	7

2.3. Phosphates kinetic studies

The sorption capacity of phosphates onto Polonite® (mgP-PO$_4$·g^{-1}) was calculated from the decrease in phosphates concentration in the liquids by following equation:

$$q_e = \frac{\left(C_{\text{in}} - C_e\right)\cdot V}{m} \tag{1}$$

where q_e is the equilibrium sorption capacity (mg·g^{-1}), V is the volume of the synthetic solution or river water (L), m is the mass of RM used (g), and C_{in} and C_e are the initial and final (equilibrium) concentrations (mg·L^{-1}).

The obtained results from SRFs box experiments were fitted to two the most widely used non-linear kinetic models: the pseudo-first-order (PFO) kinetic model (Eq. (2)) and the pseudo-second-order (PSO) (Eq. (3)) kinetic model by Lin and Wang [25], and Feizi and Jalali [26]:

$$\log\left(q_e - q_t\right) = \log q_e - kt \tag{2}$$

$$\frac{1}{q_t} = \frac{1}{q_e^2 k_2} + \frac{t}{q_e} \tag{3}$$

where q_t (mg·g^{-1}) represents the amount adsorbed at any time t, k_1 (min^{-1}) and k_2 (g·mg^{-1}·min^{-1}) are rates of sorption of the PFO and PSO, and q_e is the amount adsorbed at equilibrium (mg·g^{-1}).

The parameters of both kinetic models were obtained by Solver (Microsoft Excel). The fit of experimental data to the PFO and PSO models were checked using the correlation coefficients and mean chi-square error analysis (Eq. (4)) [27]:

$$\chi^2 = \frac{1}{n}\cdot\sum\frac{(q_t - q_e)^2}{q_e} \tag{4}$$

where n is the number of observations while q_t and q_e represent the observed sorption at any time t and the calculated by PFO and PSO models equilibrium sorption capacity, respectively.

In order to precisely determine the significance of differences between average sorption values of SS and RW experiments, the ANOVA analysis of variance Tukey's test was applied at a significance level of 0.05, with differences significant for $p < 0.050$ in Statistica 12 software by StatSoft.

3. Results

The PFO and PSO kinetic studies are important in order to evaluate the mechanism and efficiency of sorption process. Adsorption kinetics expresses the nature of adsorption interaction dependence, both physical and/or chemical, of the RM with phosphates. Sorption dynamics of tested material as a function of time and mass of RM (10, 50 and 100 g) are presented in Fig. 1. Presentation of fitting the PFO and PSO kinetic models to obtained data is in Fig. 2. The parameters of PFO and PSO are set in Table 3. Based on results obtained from modeling, the PFO and PSO kinetic models parameters (Table 3), each variant of SRFs box experiment better fit to the PSO kinetic model. This is confirmed by R^2 values which represent the measure of fitness to this kinetic model (>97%) and low value of χ^2. Also, the linear alignment between experimental q_e values and q_e calculated by the PSO model has a high correlation (R^2 = 97%) (Fig. 3).

The most rapid P-PO$_4$ removal is seen in case of 50 and 100 g of RM, especially in case of SS experiment. The unnatural shape of SS_50 g and SS_100 g curves is a result of fast initial removal of phosphate (during two first days 82% and 91% of P-PO$_4$ concentration was removed by SS_50 and SS_100, respectively). It finds confirmation at values of kinetic reaction constant k_2. The k value informs how fast and dynamic the reaction runs [12]. The higher k_2 value is obtained, the faster is the P removal process, which is confirmed by phosphates removal. The initial faster rate of phosphates removal may be due to the availability of the uncovered surface area of the sorbent initially, because a sorption kinetics depends also on the surface area of the sorbent [28]. The relationship between k_2 and phosphates removal is good (R^2 = 69%). In case of SRFs, the k_2 values of the PSO ranged between 0.2283 to 169.137, and higher values were noted for SS. The k_2 value sequence is as follows: SS_100 g > RW_100 g > SS_50 g > RW_50 g > SS_10 g > RW_10 g.

The removal of phosphates ranged from 61% (RW_10 g) to 99% (SS_100 g). Generally, higher removal was observed in SS experiment (81%; 98% and 99% for 10; 50 and 100 g of RM, respectively), then for RW (61%; 63% and 72% for 10; 50 and 100 g of RM, respectively). The phosphates unit sorption of RM was the highest in case of the smallest dosage of RM (10 g per 10 L). In case of SS experiment, unit sorption's are 3.147, 0.684 and 0.347 mg·g^{-1} for 10, 50 and 100 g of RM, respectively. For RW experiment, the unit sorption's are 1.875, 0.383 and 0.216 mg·g^{-1} for 10, 50 and 100 g of RM, respectively. However, the highest phosphate concentration removal does not correspond to highest unit sorption. The most significant removal is observed for the biggest mass of RM (99% for SS 100 g and 72% or 100 g RW). Such observation may indicate the overestimation of RM mass of SRF. The comparison of mean sorption obtained for SS and RW experiments show there is no significant ($p < 0.05$) difference between sorption obtained by 50 and 100 g of RM (Fig. 4). This confirms the statement that increasing the mass of RM from 50 to 100 g is purposeless and economically unjustified. There are also no statistically significant differences ($p < 0.05$) between mass of 50 and 100 g of both experiments.

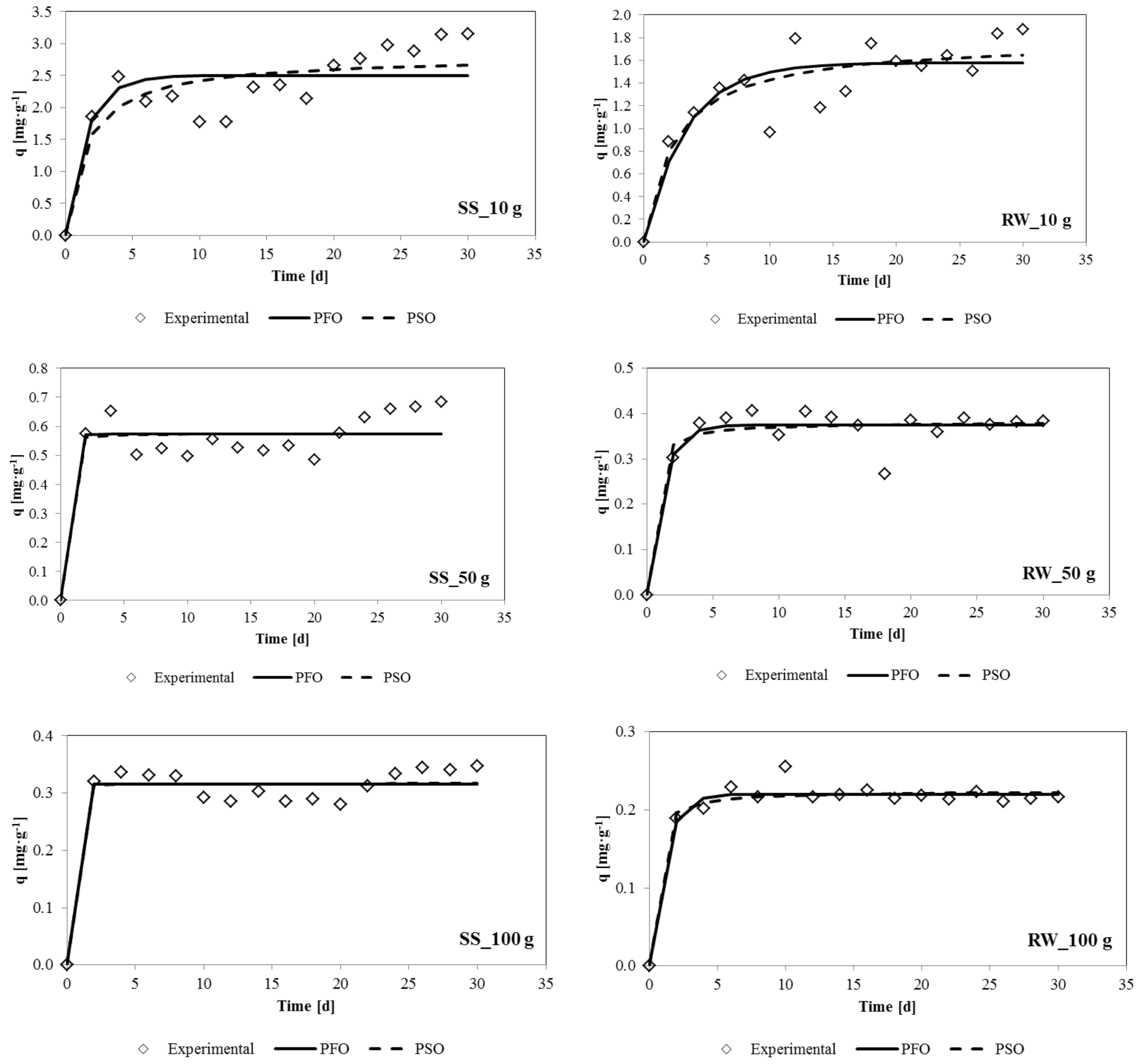

Fig. 2. Experimental data PFO and PSO for synthetic solution (SS) and river water (RW) for 10, 50 and 100 g of RM.

Table 3
Calculated parameters of the pseudo-first and pseudo-second kinetic order models

Mass of RM (g)	q_e experimental ($mg \cdot g^{-1}$)	Pseudo-first-order model				Pseudo-second-order model			
		k_1 (min^{-1})	q_e ($mg \cdot g^{-1}$)	R^2 (%)	χ^2 (%)	k_2 ($g \cdot mg^{-1} min^{-1}$)	q_e ($mg \cdot g^{-1}$)	R^2 (%)	χ^2 (%)
Synthetic solution (SS)									
10	3.147	0.6462	2.497	82.63	0.504	0.2307	2.795	97.56	0.399
50	0.684	4.3857	0.572	90.57	0.052	32.855	0.575	99.97	0.051
100	0.347	6.202	0.315	95.86	0.012	169.137	0.319	99.96	0.012
River water (RW)									
10	1.875	0.2999	1.577	87.69	0.238	0.2283	1.782	99.30	0.194
50	0.383	0.8775	0.375	94.55	0.019	8.5549	0.381	99.72	0.021
100	0.216	0.9306	0.220	98.08	0.004	15.5939	0.224	99.78	0.100

The variability of pH over the entire experiment showed the influence of mass of RM on pH value (Fig 5). The higher the mass of RM, the higher value of pH were observed. Also, the higher values were noted in case of SS experiment than RW. For SS experiment the median (min-max) pH values were 7.63 (6.85–9.70); 8.43 (6.79–10.39) and 8.66 (6.92–10.92) for 10, 50 and 100 g, respectively. The RW experiment is characterized by median (min-max) pH values: 8.21 (7.74–8.31); 8.35 (7.80–8.45) and 8.48 (7.78–8.89) for 10, 50 and 100 g, respectively.

4. Discussion

4.1. P sorption and limitations

Previous results from phosphates adsorption kinetics also follow the PSO kinetic equation as a mechanism of sorption process [28–30]. Based on conducted calculations, removal of phosphates onto Polonite® in form of SRFs follows the PSO kinetic models. Riahi et al. [29] tested date palm fibers as a low-cost biosorbent, obtained $R^2 > 99\%$ to the PSO kinetic model and the difference between the experimental and theoretical calculated sorption at equilibrium was very small (less than 1%). They tested five different initial concentrations between 30,110 mgP-PO$_4$·L^{-1} and obtain the sorption ranged from 3.805 to 5.920 mg·g^{-1} at mass to volume ratio 6 g:1 L. Elwakeel and Al-Bogami [28] evaluate the sorption kinetic properties of four natural RMs such as: marble dust, sawdust, soil, and rice husk and in this case, the kinetic process follows the PSO with $R^2 > 99\%$. They used initial concentration of 100 mg·L^{-1} that resulted in sorption of 0.21–3.88 mg·L^{-1}. The mass to volume ratio was 5 g:0.25 L. Chmielewská et al. [30] also confirmed the PSO kinetic model as a favorable one for nine RMs (biosorbent, man-made and natural sorbents) by $R^2 > 85\%$. At initial concentration of 300 mgP-PO$_4$·L^{-1}, they obtained the sorption ranged between 11.0 and 30.9 mg·g^{-1} for mass to volume ratio of 0.3 g:0.3 L.

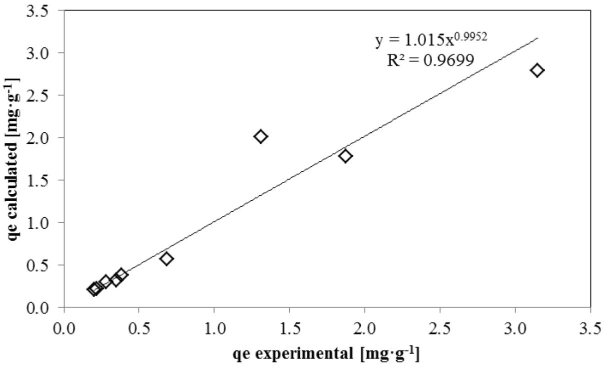

Fig. 3. Relationship between PSO modeled (q_e calculated) and experimental (q_e experimental) sorption capacity.

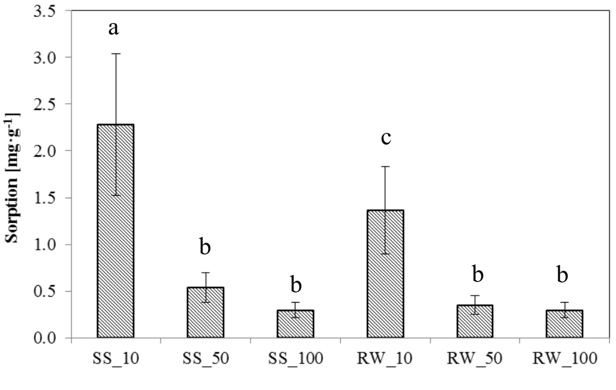

Fig 4. Mean sorption of P-PO$_4$ in SS and RW experiments. Columns with error bars indicate the average values with standard deviation. Bars marked with different letters differ significantly ($p < 0.05$) according to Tuckey test.

Following the reaction by the PSO kinetic model suggests that chemisorption is the rate-limiting step [11,28,29]. Riahi et al. [29] claim, the adsorption of phosphate species can be reasonably speculated to occur in two steps: transfer of phosphate from the aqueous solution to the sites on the RM and chemical complexation or ion exchange at the active sites and precipitation on the RM surface.

The observed pH increasing is probably a result of formation of HPO_4^{-2} which is dominant species at pH ranged from 7 to 12 [31]. Lee et al. [32] and Khelifi et al. [33] claim that chemical precipitation process is dominant where the pH has values above 8. Also Chen et al. [34] claims that a chemical precipitation mechanism may be the predominant process at high initial pH in aqueous solution. Lower pH values were observed in case of RW than SS experiment which may be resulted by buffer capacity. The buffer capacity of RW prevented the rise of the pH value above 8.89 (RW_100 g) and it stayed between 7.74 and 8.89 over the entire period of the experiment. In case

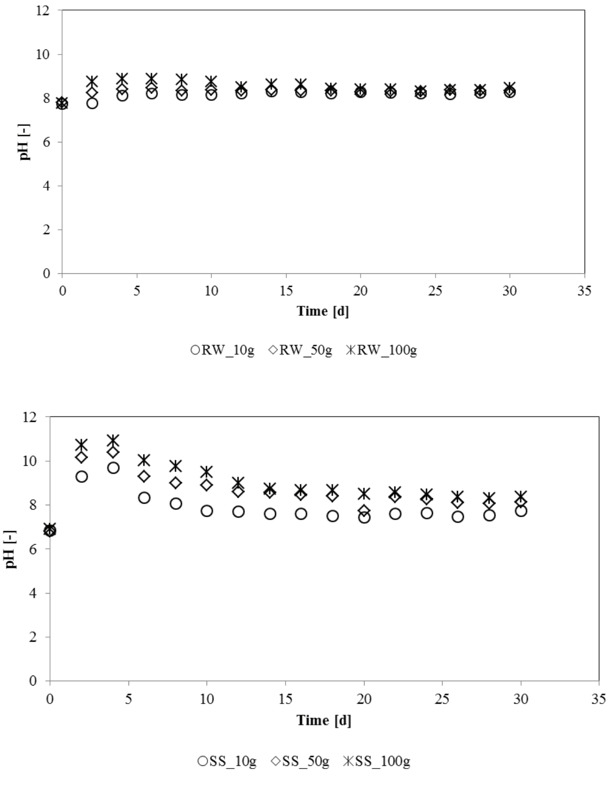

Fig. 5. pH variability over the experiment time of synthetic solution (SS) and river water (RW) for 10, 50 and 100 g of RM.

of SS experiment, the pH was ≈10 at the beginning of the experiment since the P solution did not have any buffer capacity and decreased fast to ≈8 toward the end of the experiment. Ádám et al. [35] noted similar observation with buffer capacity with shell sand and Filtralite P® as a phosphorus RM.

RW experiment has a lower phosphates sorption due to contaminations present in the water. Surface water contaminations such as biogens (nitrogen and phosphorus), heavy metals (Ba, Cr, Cu, Ni, Zn), organic (humic acids) and inorganic anions (nitrate, sulfate), pharmaceuticals, etc., may influence on reduction of P sorption properties or even cause P desorption [30]. SRFs with RW are characterized by lower sorption of 38%–44% than the same mass to volume variant of SS experiment. This also corresponds to decreasing of P concentration removal of 18%, 16%, and 5% for 100, 50, and 10 g, respectively. What is more, the contamination of river water decreases the kinetic constant k_2 of 0.002–153.543 g·mg^{-1} min^{-1}. Zhang et al. [36] also claim that the existence of the interfering ions decreases the adsorption capacity of lanthanum-doped activated carbon fiber (ACF-La) and the order of negative influence on the phosphates adsorption is: $CO_3^{2-} > NO_3^- > SO_4^{2-}$. The probable explanation is that competition exists between interfering ions and phosphates for binding to the active sites and CO_3^{2-} ions may have a strong affinity toward the active sites of the sorbent in compared with NO_3^- and SO_4^{2-}. Phosphates sorption on ACF-La follows the PSO kinetic and the interfering ions presented in solution reduce the overall rate constant of PSO adsorption (k_2) from 0.0169 to 0.0036 g·mg^{-1} min^{-1}. They suggest that the presence of interfering ions may prevent the phosphates from adsorbing onto ACF-La. The negative effect of anions (nitrate, sulfate, and biocarbonate) on phosphate sorption was also noted by Kang et al. [37] for autoclaved aerated concrete (AAC). Phosphates sorption decreased with increasing the anions concentration from 1 to 10 mM, and the competing anions effect is $HCO_3^- > SO_4^{2-} > NO_3^-$. On the other hand, Ren et al. [38] prove that there is only a slight decrease in phosphates removal on an iron–zirconium binary oxide by increasing concentration (from 1.0 to 10 mM) of coexisting anions such as chloride, sulphate, and carbonate by competitive adsorption. This observation suggests that this binary oxide has high adsorption selectivity toward phosphates anions and has high potential to be used as a RM in real water and wastewater.

The other limitation factor in case of sorption is a temperature. Yuan et al. [39] observed the phosphate removal by dolomite decreased with the increase of adsorption temperature (from 20°C to 80°C), in case of high initial phosphate concentration (from 10 to 90 mg P-PO$_4$·L^{-1},). They indicated that phosphate adsorption on the dolomite is exothermic reaction. Also, Abdelhay et al. [40] confirmed this observation for *Arundo donax* reeds as a RM. The increase in temperature from 25°C to 45°C had a negative effect on the adsorption of phosphate. They also concluded that the sorption process of phosphate is of exothermic nature. The same observation of decreasing sorption properties with increasing the process temperature noted Eljamal et al. [27] for As(V).

4.2. SRF comparison

SRFs have been already tested in stagnant water conditions with AAC as a RM [5] and in a recirculating flow condition [6,18] with both Polonie® and AAC. Stagnant water conditions (a box experiment) favor better unit sorption than flowing (a recirculating) system. 1 g of AAC removed 2.53 mgP-PO$_4$·g^{-1}, 0.58 mgP-PO$_4$·g^{-1} and 0.30 mgP-PO$_4$·g^{-1} at mass to volume ratio of: 1 g:1 L, 5 g:1 L and 10 g:1 L, respectively [5]. The pervious experiment was also conducted at stagnant water condition with synthetic solution of initial P-PO$_4$ concentration 2.972 mgP-PO$_4$·L^{-1} ± 0.120. AAC box experiment has lower sorption properties than Polonite® (this study) of 13%–20%. The biggest difference in unit sorption was obtained in case of the smallest mass of RM (10 g). The recirculating flow condition experiments were conducted with synthetic P solution. In case of Polonite®, the study was conducted for four initial concentrations (1.439, 1.852, 2.384 and 3.012 mg·L^{-1}) and resulted in unit sorption ranged from 0.166 to 0.181 mg·g^{-1}, average 0.177 mg·g^{-1} ± 0.007. What is more, 1,200 g of AAC used as a SRFs during 30 d decreased the P initial concentration from 1.335 mg·L^{-1} to the 0.190 mg·L^{-1} which corresponds to 85% of reduction [6]. It corresponds to the unit sorption of 0.382 mg/g. Both recirculating experiments were set up with mass to volume ratio of 3 g:1 L. However, it has to be kept in mind that previous SRFs experiments were set up only with synthetic P solution that promotes P sorption. It is highly probable that river water conditions may decrease the sorption properties.

4.3. Application recommendations

Obtained results allow to stimulate P removal process by choosing an appropriate mass to volume ratio of RM to treated water. Depending on predicted results, fast removal from water or long-lasting sorption properties of material, the mass of RM may be adjusted. At the moment of sudden P appearance (‘hot moment’) after heavy rainfall, the ratio of 5 g:1 L gives us promising results (94% and 64% concentration removal for SS and RW along 4 d, respectively). Further increasing of the mass of RM does not result in expected increase of P removal. The difference of P removal in case of 50 and 100 g equals 1% and 10% of SS and RW experiment, wherein the mass of RM is increased of 100%. From economical point of view, doubling of RM mass is unprofitable. In case of places where occur a constant supply of P to the water the recommended mass to volume ratio is 1 g:1 L. The examples of possible implementations can be, for example, endangered areas of storage or high concentration of nutrients such as dairy farms, or areas affected by mineral fertilization or manure application (‘hot places’). RM longevity (the maximum sorption properties is estimated on 96.58 g·kg^{-1}) and high unit sorption properties (3.147 and 1.875 mg·g^{-1} for SS and RW experiments, respectively) make implementation of this material in such places beneficial.

SRFs were predicted to be implemented to treat non-point sources of contamination (at agriculture areas) which are difficult to reduce in the view of large scale affected where ‘end of pipe’ technology cannot be applied. The systems of SRFs is able to be used in case of small water bodies in rural areas (small streams, drainage ditches, small field ponds), however there are other applications of curtains consist of SRFs, for example, swimming and backyard ponds, stormwater retention ponds localized at urban areas, additional step to P removal of on-site wastewater treatment plant and support system to increase the P removal of constructed wetland.

5. Conclusion

The adsorption mechanism of removing phosphate by Polonite® follows the pseudo-second-order kinetic model that provides the chemisorption is the main sorption mechanism. In case of river water, the unit sorption of phosphate was around 40% lower than sorption from solution. The highest unit sorption obtained for the smallest dose (10 g) of RM (3.147 and 1.875 mg·g^{-1} for SS and RW experiments, respectively) suggests that bigger filters are oversized. Increasing of RM mass increase the overall phosphate removal but do not increase the unit sorption. For these reasons, the recommended mass to volume ratio of RM to treated water is 1 g:1 L. It gives the long lasting sorption performance of RM and high unit sorption. In case of fast and rapid phosphates removal priority, the recommended mass of RM to volume ratio is 5 g:1 L. The further increase of RM mass do not give satisfactory results (lower sorption than in case of 50 g and slight increase of phosphate removal efficiency) and is not economically reasonable.

Symbols

C_{in} — Initial concentration, mg·L^{-1}
C_e — Final (equilibrium) concentration, mg·L^{-1}
k_1 — Rate of sorption of the pseudo-first-order kinetic model, min^{-1}
k_2 — Rate of sorption of the pseudo-second-order kinetic model, g·mg^{-1} min^{-1}
m — Mass of RM, g
n — Number of observations
q_e — Equilibrium sorption capacity, mg·g^{-1}
q_t — Sorption at any time t, mg·g^{-1}
P — Phosphorus
PFO — Pseudo-first-order
PSO — Pseudo-second-order
R^2 — Coefficient of determination
RM — Reactive material
RW — River water
SS — Synthetic solution
SRFs — Suspended reactive filters
V — Volume, L
χ^2 — Mean chi-square error

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