



THE EFFICIENCY OF FILTRATION MATERIALS (POLONITE® AND LECA®) SUPPORTING PHOSPHORUS REMOVAL IN ON SITE TREATMENT SYSTEMS WITH WASTEWATER INFILTRATION

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Abstract

The most of the on site wastewater treatment systems in Poland discharges treated effluent to the soil. The goal of phosphorus (P) reduction from dispersed sources of pollution can be achieved by application of P reactive materials in the construction of wastewater infiltration systems.

Two P reactive materials were tested in this study: Polonite® in grains of 2÷6 mm and lightweight aggregate Leca® in grains of 4÷10 mm. Apparent P sorption capacity was assessed on 40.9 mg·g⁻¹ (Polonite®) and 5.1 mg·g⁻¹ (Leca®). Both materials sorbed P-PO₄ very fast, after 15 min over 90% of P was removed from solution and wastewater. Wastewater used in this study came from the outlet from the septic tank of on site septic system. P-PO₄ solution was prepared from KH₂PO₄ and the tap water. In the small column experiment, four columns (2 filled with Polonite® and 2 filled with Leca®) were fed with wastewater and P-PO₄ solution in hydraulic loadings of 30÷40 dm³·m⁻²·d⁻¹. All the columns removed significant amounts of P from both solution and wastewater with the reduction between 28.3% and 72.5%. The mean P-PO₄ effluent concentrations ranged from 1.21 mg·dm⁻³ to 7.12 mg·dm⁻³. The best

overall performance was achieved by the Polonite® fed with solution. Both tested materials can support wastewater treatment in on site systems.

Keywords: phosphorus, reactive material, on site wastewater treatment, infiltration system

INTRODUCTION

On site treatment systems are used worldwide to treat domestic wastewater from individual households in rural and peri-urban areas that are not connected to main sewage networks. Septic tank systems (STS), typically comprise the septic tank and the piped drainfield, are the most common form of on site treatment, however the popularity of the more advanced technologies e.g. activated sludge, biological film, sand filters or constructed wetlands increases. On site treatment offers several advantages over more centralized systems in terms of energy efficiency and costs. STS, for example have also very low greenhouse gas emissions (Withers *et al.* 2014). Regardless of the used technology, in most cases wastewater treated on site is discharged to soil as a final receiver.

Those dispersed small point sources of pollution can cause a large impact on soil, ground water and local stream chemistry. Most studies show that P can be immobilized in soil under the drainfield, however it can be transported in the subsurface when longer time period is considered (Hartman *et al.* 1996, Eveborn *et al.* 2014). Halicki and Szustakowski (2003) reported the impact of wastewater discharged to soil on groundwater quality. They found that P-PO₄ concentration in groundwater at the area of the household varied between 0.97 and 2.45 mg·dm⁻³ while P-PO₄ concentrations were as low as 0.02 mg·dm⁻³ at the area without any settlings. Withers *et al.* (2011) reported P-PO₄ concentration of 0.004÷1.208 mg·dm⁻³ and 0.139÷2.028 mg·dm⁻³ in local streams affected by STS. The contribution of STS to total nutrient loading at catchments scale is highly dependent on STS density (Withers *et al.* 2012).

P concentration in wastewater discharged from on site treatment systems located outside of agglomerations is not limited by Polish regulations (Dz.U. 2014 poz. 1800). From the review of the literature it can be stated that those values vary in a wide range (tab. 1).

One of the options of increasing the efficiency of P removal from small wastewater streams is the use of P reactive materials, e.g. by underlying of the drainpipe discharging wastewater from on site treatment system to the soil. The goal of this study was to assess the potential environmental effect of implementation of P reactive material layer as a part of wastewater infiltration system.

Table 1. Phosphorus and phosphate concentration in effluent from on-site wastewater treatment systems

Concentration	Load	Treatment	References
4.0÷53.7 mgP·dm ⁻³	22.2 mgP·d ⁻¹	biological	Bugajski 2009
2.1÷29.5 mgP·dm ⁻³	9.8 mgP·d ⁻¹	biological	Bugajski 2009
2.5÷55.0 mgP·dm ⁻³	18.5 mgP·d ⁻¹	biological	Bugajski 2009
8.9÷72.8 mgP·dm ⁻³	111 mgP·d ⁻¹	biological	Bugajski 2009
2.5÷9.7 mgP·dm ⁻³	n.d.	biological	Markowska and Michałowski 2007
2.8÷9.9 mgPO ₄ ·dm ⁻³	n.d.	biological	Jucherski <i>et al.</i> 2017
0.195÷20.560 mgP·dm ⁻³ 0.055÷6.760 mgP-PO ₄ ·dm ⁻³	n.d.	mechanical	Withers <i>at al.</i> 2011
1.0÷11.6 mgP-PO ₄ ·dm ⁻³	n.d.	mechanical	Hartman <i>et al.</i> 1996
14.0÷50.0 mgP-PO ₄ ·dm ⁻³	n.d.	mechanical	Jucherski and Walczowski 2001
n.d. – no data			

MATERIALS AND METHODS

Tested materials

In this study, two materials were tested: Polonite® in grains of 2÷6 mm (Ecofiltration Nordic AB) and Leca® in grains of 4÷10 mm (Saint-Gobain Construction Products Polska sp. z o.o.). The Polonite® is a natural, processed mineral – a calcium silicate – with excellent capabilities of capturing phosphorus from both sewage water and runoff water from farmland (<http://www.ecofiltration.se/en/reactive-filter-media>). The Leca® is a lightweight construction material used in civil engineering, geoinforming, agriculture, horticulture and environmental protection (<http://leca.pl/produkty>). Materials are different in chemical composition, physical properties and also in price (tab. 2). Polonite® is dedicated to be used for P removal from water and wastewater, for Leca® it is an option for alternative application.

Wastewater and P-PO₄ solution

For batch sorption tests and column experiment two type of media carrying P-PO₄ were used. The first one was the solution prepared from KH₂PO₄ and the tap water. The second one was mechanically treated wastewater sampled from the outlet of the septic tank in on-site wastewater treatment system.

Table 2. Characteristics of tested materials

Material	Polonite [®]	Leca [®]
Grain size [mm]*	2÷6	4÷10
Chemical composition*	CaO (42.6%), SiO ₂ (40.2%)	n.d.
pH	> 12*	7.5
P-PO ₄ (in H ₂ O extract) [mg·kg ⁻¹]	0	0.3÷1.9 (av. 0.97)
P-PO ₄ (in HCl extract) [mg·kg ⁻¹]	0	2.8÷7.1 (av. 4.36)
Dry density [kg·m ⁻³]*	730	320±15%
Porosity [%]	38	48
Price*	1460 zł·m ⁻³	400 zł·m ⁻³

* data from the manufacturer, n.d. – data not available

Sorption isotherm and sorption kinetic

For the estimation of P sorption capacity of tested materials, the artificial P solution was used in concentrations varying from 1 to 1,100 mg P-PO₄·dm⁻³. The triplicate samples of both materials were shaken in glass flasks, each contained 1 g of reactive material and 0.1 dm³ of the various phosphorus solution for 24 hours. The P-PO₄ sorption was calculated based on the difference of load of P added and obtained in a filtered sample. Obtained data were fitted to Langmuir isotherm (Al Duri 1996) in Statgraphics Centurion XVI v.16.0.007 for estimation of apparent P sorption capacity.

For the estimation of sorption kinetics triplicate 1 g samples of materials were shaken in contact time amounted 15, 30, 45, 60, 90 minutes and 3, 5, 24, 48, 72 and 77 hours with 0.1 dm³ of solution and wastewater. The initial concentrations of solution and wastewater were 11.42 and 15.58 mg P-PO₄·dm⁻³ respectively. Samples were filtered and analyzed on FIAstar 5000 Analyzer by ammonium molybdate method in two ranges 0.005÷1 mg P-PO₄·dm⁻³ and 0.1÷5 mg P-PO₄·dm⁻³ depend on phosphate concentration in extract.

Column experiment

The column experiment was designed to simulate the hydraulic load of wastewater discharged to the soil via infiltration system. Experiment consisted of 4 columns with the inner diameter of 6.4 cm and height of 21 cm. Columns were filled with 10 cm layer of tested materials underlined with geotextile. Columns C1 and C2 were filled with Polonite[®] (270g each), while C3 and C4 with Leca[®] (95g each). Columns C1 and C3 were fed with P-PO₄ solution (tank 1), C2 and C4 with pretreated wastewater (tank 2) (fig. 1). The 4 channel peristaltic pump Lead Fluid[®] BT100S (Lead Fluid Technology co, LTD) was used to

transport of solution and wastewater from tanks 1 and 2. The flow was set to simulate hydraulic load of $40 \text{ dm}^3 \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ (5mL per 1min at 10 rpm and 55 min brake, 25÷26 cycles per day), however during the experiment it was observed that pump channels do not work evenly. As the result hydraulic load of different columns was $40 \text{ dm}^3 \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ for C1, $30 \text{ dm}^3 \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ for C2, $35 \text{ dm}^3 \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ for C3 and $30 \text{ dm}^3 \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ for C4. Leachates from columns were collected in glass containers for volume control and sampled for analyses. Samples of solution, wastewater and leachates from columns were analyzed for P-PO_4 concentration. The experiment run for 127 days in total, but the real time of feeding the columns amounted 60 days

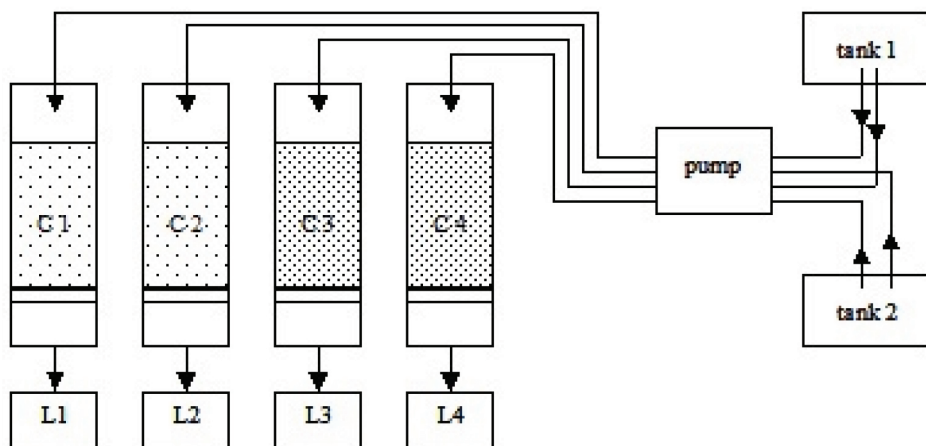


Figure 1. The set up of the experiment. Tank 1: P-PO_4 solution, tank 2: pretreated wastewater, C1: Polonite[®] fed with solution, C2: Polonite[®] fed with wastewater, C3: Leca[®] fed with solution, C4: Leca[®] fed with wastewater, L1, L2, L3, L4: leachate containers

RESULTS

Both tested materials can be classified as P-reactive (Cucarella and Renman 2009), however the Polonite[®] has higher sorption capacity than the Leca[®]. Examining the course of phosphorus removal from the solution it can be stated that for the Leca[®] apparent P sorption capacity was obtained in the batch test (Fig. 2) while in case of the Polonite[®] the smoothing of the curve was not achieved (Fig. 2). It means that the P sorption capacity of the material can be higher. Results from the batch isotherm test for both materials fitted by Langmuir equation gave the P-PO_4 sorption capacity of $40.9 \text{ mg} \cdot \text{g}^{-1}$ and $5.1 \text{ mg} \cdot \text{g}^{-1}$ for the Polonite[®] and the Leca[®], respectively.

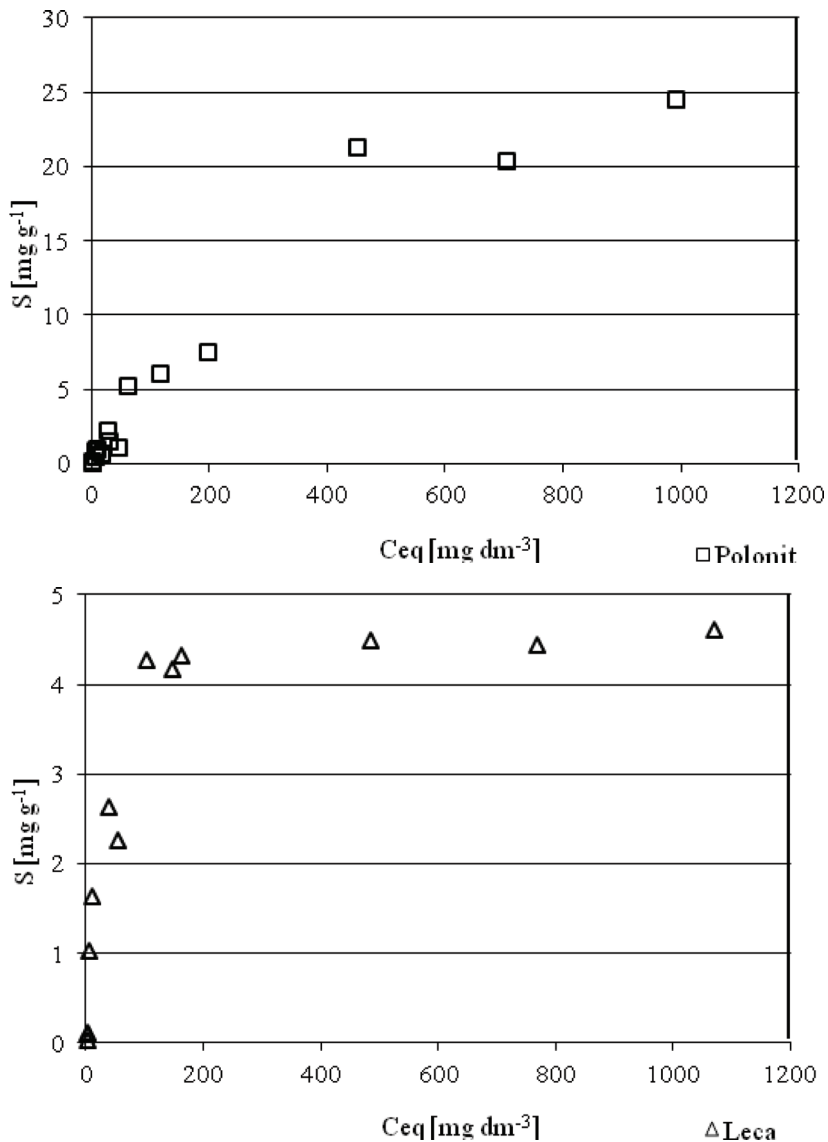


Figure 2. Sorption of P-PO₄ by the Polonite[®] and the Leca[®]

Opposite to sorption capacity, there was any difference observed between materials in case of the sorption kinetics, as both of them were able to bind phosphorus in short time. After 15 minutes of the contact time both materials removed over 90% of P-PO₄ from the solution and wastewater (Fig.3).

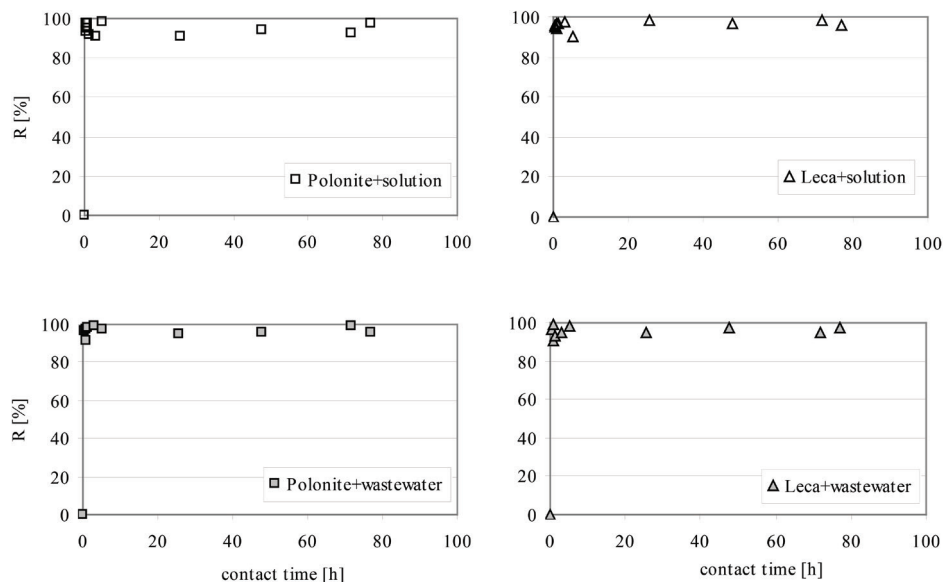


Figure 3. Sorption kinetics tests with the Polonite[®] and the Leca[®]

Column experiment

The initial hydraulic loading rate was set on $40 \text{ dm}^3 \cdot \text{m}^2 \cdot \text{d}^{-1}$ what is suitable value for sandy soils. At the beginning all columns were fed with the same amount of wastewater or solution. Unfortunately, from the 78 day of experiment due to discalibration of peristaltic pump hydraulic loads varied between filters, what resulted in the difference of P loads in columns C1 and C3 (tab. 3). The P-PO_4 concentration of solution and wastewater varied within the period of experiment in the range of $0.29 \div 16.75 \text{ mg} \cdot \text{dm}^{-3}$ (solution) and $2.22 \div 20.87 \text{ mg} \cdot \text{dm}^{-3}$ (wastewater) what reflects the values reported in the literature review (tab.1). Due to the grains of the materials of $2 \div 6 \text{ mm}$ (Polonite[®]) and $4 \div 10 \text{ mm}$ (Leca[®]) the residence time of wastewater in the saturated filter was very short. The drops of effluent appeared few seconds after the pump started. All the more so observed P removal efficiency of $52.8 \div 72.5\%$ for Polonite[®] and $28.3 \div 31.7\%$ for Leca[®] is high. In the full scale infiltration system, wastewater will be down-turn by the site soil with the lower permeability. That will significantly increase the contact time between the wastewater and the filter and as the result the P reduction from wastewater can be even higher. In terms of overall P reduction, the Polonite[®] was more effective in P removal than the Leca[®], what confirms the insights from the isotherm batch experiment. Polonite[®] fed with P-PO_4 solution gave the best results in terms of effluent concentrations. The maximum observed

value was $4.85 \text{ mg}\cdot\text{dm}^{-3}$ and the removal efficiency was much higher than in column filled with Leca[®] fed with the same solution.

Table 3. The P-PO₄ concentrations, total loads in solution/wastewater applied to filters and detected in leachates; reduction of P-PO₄ and unit P sorption on the filters

C_{in} [$\text{mg}\cdot\text{dm}^{-3}$] mean (min÷max)	C_{out} [$\text{mg}\cdot\text{dm}^{-3}$] mean (min÷max)	Tot L_{in} [mg]	Tot L_{out} [mg]	R [%]	Unit sorption ($L_{in}-L_{out}$) [$\text{mg}\cdot\text{g}^{-1}$]
C1: Polonite [®] fed with P-PO ₄ solution					
4.41 (0.29÷16.75)	1.21 (0÷4.85)	33.44	9.21	72.5	0.09
C2: Polonite [®] fed with wastewater					
10.69 (2.22÷20.87)	4.85 (0.85÷13.90)	72.83	34.39	52.8	0.14
C3: Leca [®] fed with P-PO ₄ solution					
4.41 (0.29÷16.75)	3.27 (0.16÷14.43)	32.48	23.30	28.3	0.10
C4: Leca [®] fed with wastewater					
10.69 (2.22÷20.87)	7.12 (1.80÷15.77)	72.83	49.74	31.7	0.24

Comparing the P removal behavior by the Polonite[®] in case of P-PO₄ supplied with wastewater and solution is difficult as the total initial load and concentrations were different, but in case of column fed with solution efficiency was higher than in case of column fed with wastewater. Unit sorption in this case was similar, what suggests that the efficiency does not depend on initial concentration and load of P. Columns filled with the Leca[®] gave the similar results in terms of P removal independently from the form of liquid supplied, but obtained unit sorption is higher in case of higher initial P load.

DISCUSSION

Both tested materials are P reactive. According to Cucarella and Renman (2009) filtration materials with the P sorption capacity between 1 and $10 \text{ g}\cdot\text{kg}^{-1}$ (Leca[®] $5.1 \text{ g}\cdot\text{kg}^{-1}$) have high and with P sorption capacity, and $10 \text{ g}\cdot\text{kg}^{-1}$ (Polonite[®] $40.9 \text{ g}\cdot\text{kg}^{-1}$) very high sorption capacity. Obtained values of P sorption for Leca[®] are similar to those found in other batch studies. Leca[®] from Estonia had sorption capacity of $7.98 \text{ mgP}\cdot\text{g}^{-1}$ (Vohla *et al.* 2005), lightweight aggregate LWA from USA $3.465 \text{ mgP}\cdot\text{kg}^{-1}$ (Zhu *et al.* 1997), however also lower values are reported e.g. LWA from Norway $46\div565 \text{ mg}\cdot\text{kg}^{-1}$ (Zhu *et al.* 1997). For the Polonite[®] the noted values were as high as $79\div182 \text{ gP}\cdot\text{kg}^{-1}$ for fine fraction (Cucarella *et al.* 2007) but at average amounts $12.3\div25.5 \text{ mgP}\cdot\text{g}^{-1}$ (Bus and Karczmarczyk 2014).

The highest reported sorption of material in the grain size available for filtration (2÷5(6) mm) was $94.32 \text{ mg}\cdot\text{g}^{-1}$ (Karczmarczyk and Bus 2014).

Hydraulic loading rates of $30\div 40 \text{ dm}^{-3}\cdot\text{m}^2\cdot\text{d}^{-1}$ used in this study reflects the suggested values for sizing infiltration surfaces (EPA/625/R-00/008 2002, Błażejowski 2003). The value of $40 \text{ dm}^{-3}\cdot\text{m}^2\cdot\text{d}^{-1}$ is appropriate for sands receiving wastewater with BOD_5 concentration of $30 \text{ mg}\cdot\text{dm}^{-3}$. In case of higher BOD_5 concentrations suggested hydraulic loading rates are lower. Hydraulic loadings and following retention time can influence P removal efficiency of infiltration systems (Li *et al.* 2012, Herrmann *et al.* 2013). Li *et al.* (2012) observed negative effect of increasing hydraulic loading on total phosphorus (TP) removal efficiency. In the range of $40\div 125 \text{ dm}^{-3}\cdot\text{m}^2\cdot\text{d}^{-1}$, the suggested optimal hydraulic loading for TP removal was at $81 \text{ dm}^{-3}\cdot\text{m}^2\cdot\text{d}^{-1}$. Kholoma *et al.* (2016) reported the efficiency of wastewater infiltration system supported with the mixture of 3 different materials: washed sand ($d_{10} = 0.3 \text{ mm}$), gas concrete (Sorbulite[®], 10-80 mm) and charcoal in the range of hydraulic loadings of $16\div 23 \text{ dm}^{-3}\cdot\text{m}^2\cdot\text{d}^{-1}$. From initial average TP concentration of $8.67 \text{ mg}\cdot\text{dm}^{-3}$ they obtained effluent concentration from sand of $6.70 \text{ mg}\cdot\text{dm}^{-3}$. The same sand with the charcoal decreased TP concentration to $6.63 \text{ mg}\cdot\text{dm}^{-3}$, and the gas concrete to $6.11 \text{ mg}\cdot\text{dm}^{-3}$. The filters generally failed to meet effluent quality criterion of $1 \text{ mg}\cdot\text{dm}^{-3}$ but unit sorptions of P were high: $23.9 \text{ mg}\cdot\text{kg}^{-1}$ (reduction of 40.2%) for gas concrete with biochar, $10.2 \text{ mg}\cdot\text{kg}^{-1}$ (25.6%) for sand with charcoal and $4.5 \text{ mg}\cdot\text{kg}^{-1}$ (19.3%) for sand (Kholoma *et al.* 2016). The estimation of the hydraulic rate was not the goal of this study, but within the tested range of $30\div 40 \text{ dm}^{-3}\cdot\text{m}^2\cdot\text{d}^{-1}$ observed treatment efficiency was high despite that retention time in the column experiment was only in seconds. In natural conditions the underlying site soil with the lower hydraulic conductivity will slow down the wastewater outflow and as a consequence retention time in filtration layer will increase what can result in higher P removal efficiency.

In standard wastewater infiltration system the drainpipe lays on the layer of gravel. The pores between grains allow proper distribution of wastewater to the site soil. Gravel however will not play a role in removal of P from wastewater. The materials tested in this study can increase the P removal efficiency of on site wastewater treatment systems when implemented in filtration layer.

Both tested materials were able to remove P in short contact times, but for wastewater infiltration systems also P sorption capacity is important factor, as those systems should work efficient for a long time without replacing of filtration media. As the Polonite[®] is characterized by eight times higher P sorption capacity it is also supposed to be effective for longer time. From the environmental point of view the use of Polonite[®] would be more profitable. But, in case of on site wastewater treatment systems the construction costs are also very important. Table 4 sets up the calculations of the volume and the mass of filtration material

necessary to fill up 10 cm layer on the length of 60 m (3 lines 20 m each) and the width of 0.5 m. Due to the high dry density of the Polonite® the cost of needed material is very high (tab. 4). However, if we compare the costs of P removal in such system, we will find that the Polonite® is more advantageous. To reduce the construction costs of infiltration system, the use of the thinner layer of the Polonite® could be considered.

Table 4. The cost and environmental benefits of the implementation of Polonite® and Leca® as a filtration materials in STS.

Volume of filtration layer [m ³]	Total mass of filtration material [kg]	Cost of filtration layer [zł]	Potential mass of P removed [kg]	Unit cost of P removed [zł·kgP ⁻¹]
<i>Polonite®: dry density 730 kg·m⁻³, unit cost 2 zł·kg⁻¹, P sorption capacity 40.9 g·kg⁻¹</i>				
3	2190	4380	89.57	48.9
<i>Leca®: dry density 320 kg·m⁻³, unit cost 400 zł·m⁻³, P sorption capacity 5.1 g·kg⁻¹</i>				
3	960	1200	4.90	244.9

CONCLUSIONS

1. By underlying the wastewater distribution pipe with the 10 cm layer of tested materials it is possible to obtain the environmental effect in the form of P removal of 89.57 and 4.90 kg P-PO₄ for the Polonite® and the Leca® respectively. This is however theoretical value calculated base on apparent P sorption capacity of tested materials. In practice the overall P sorption can be influenced by the quality of treated wastewater.
2. In laboratory scale batch experiments there was no difference between the rate of P reduction in short contact times from wastewater and solution in case of both tested materials. However in the small column experiment some difference in P reduction from wastewater and P solution was observed.
3. In general, all the columns removed significant amounts of P from both solution and wastewater with the reduction between 28.3 and 72.5%. The mean P-PO₄ effluent concentrations ranged from 1.21 mg·dm⁻³ (C1) to 7.12 mg·dm⁻³ (C4). The best overall performance was achieved by the Polonite® fed with solution (C1).

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