The use of reactive material for limiting P-leaching from green roof substrate
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ABSTRACT
The aim of the study is to assess the influence of drainage layer made of reactive material Polonite® on the water retention and P-PO₄ concentration in runoff. A column experiment was performed for extensive substrate underlined by 2 cm of Polonite® layer (SP) and the same substrate without supporting layer as a reference (S). The leakage phosphorus concentration ranged from 0.001 to 0.082 mg P-PO₄·L⁻¹, with average value 0.025 P-PO₄·L⁻¹ of S experiment and 0.000–0.004 P-PO₄·L⁻¹ and 0.001 P-PO₄·L⁻¹ of SP experiment, respectively. The 2 cm layer of Polonite® was efficient in reducing P outflow from green roof substrate by 96%. The average effluent volumes from S and SP experiments amounted 61.1 mL (5.8–543.3 mL) and 46.4 mL (3.3–473.3 mL) with the average irrigation rate of 175.5 mL (6.3–758.0 mL). The substrate retention ability of S and SP experiments was 65% and 74%, respectively. Provided with reactive materials, green roof layers implemented in urban areas for rain water retention and delaying runoff also work for protection of water quality.

Key words | extensive substrate, green roofs, phosphorus, Polonite®

INTRODUCTION
Green roofs are constructions covered with vegetation used as a method of recovering and increasing biologically active spaces in urban areas. The main function of green roofs is retention and slowing down the outflow of rainwater, improvement of bio-climatic conditions and increasing of green area in urban landscape (Getter & Rowe 2006; Burszta-Adamiak & Mrowiec 2013). Due to the thickness of the substrate layer and planted vegetation, the roofs can be divided into extensive and intensive.

Water quality runoff from a green roof was a subject of numerous studies (Moran et al. 2005; Hathaway et al. 2008; Mendez et al. 2011; Teemusk & Mander 2011; Karczmarczyk et al. 2012; Burszta-Adamiak 2014). It is expected that green roof structures have a positive effect on runoff quality. Factors influencing the quality of the green roof’s runoff are: type and composition of artificial plant growing medium (substrate), thickness of the substrate layer, type of vegetation cover, roof age, atmospheric deposition, bird droppings and roof maintenance (Czemiel Berndtsson et al. 2009; Karczmarczyk et al. 2012; Burszta-Adamiak 2014). The main sources of P in green roof runoff are: the type of substrate (mainly organic matter content) and fertilization (Czemiel Berndtsson et al. 2009; Burszta-Adamiak 2014). Atmospheric deposition can also be an important source of P in green roof runoff (Hou et al. 2012). However, different studies show that the mass loading of phosphorus in green roof runoff is higher than in the rainfall (Moran et al. 2003; Hou et al. 2012), which indicates that P is leaching from soil medium, especially if it consists of compost, which serves as an additional source of P in the system. A substrate providing proper growth and development of plants consists of mineral (e.g. sand, gravel, brick, rubble) and organic parts (e.g. bark, peat, compost) mixed in an appropriate ratio. Therefore, water leaching from green roofs can be polluted with heavy metals (e.g. Pb, Cd), nutrients (N and P), dissolved organic carbon and suspended solids. The construction materials can also influence the pH, electronic conductivity, color, total hardness and turbidity of the runoff (Burszta-Adamiak 2014).

Some of the studies show that green roofs can be a source of phosphorus in runoff and therefore can pollute water receivers and cause their quality to deteriorate. Even an addition of 1 g of P can promote the growth of up to 100 g of algae, which represents the principal trigger of the eutrophication and toxic blue-algae blooms in the surface water (Drizo 2012). Previously, the studies on P concentration in green...
The P concentration in the runoff from green roofs can range from 0.01 mg P·L⁻¹ for green roofs covered by leaves, trees and bushes with AquaSoil substrate (inorganic lightweight soil made from perlite) underlined with plastic drainage (Czemiel Berndtsson et al. 2009) to as high as about 20 mg P·L⁻¹ for green roofs without plant cover with the commercial substrate DAKU, which is based on natural inorganic volcanic material, compost, and organic and inorganic fertilizers (Vijayaraghavan et al. 2012).

The common drainage materials used in green roof constructions are: natural materials (gravel, crushed rock, crushed lava, etc.), recycled materials (crushed brick, shredded tires, tumbled glass, etc.) and manufactured aggregates (LECA, Polytag®, slags, etc.). One of the solutions to limit P concentration in runoff from green roofs is to underline the substrate with P-reactive material as a drainage layer. The role of reactive drainage material is not only to store the amount of water and retain it for dry periods but also to sorb P leaching from the vegetation layer.

The aim of the study is to assess the influence of drainage layer made of reactive material Polonite® on the water retention and P-PO₄ concentration in runoff.

**METHODS**

**Material**

Green roof substrates are usually a mixture of mineral and organic compounds to support plant growth. The substrate used in the column experiment was described by Karczmarczyk et al. (2014). The substrate is dedicated for extensive green roofs, prefabricated in Poland and supplied by a local company in Warsaw.

Polonite® is a well-known reactive material with proved phosphorus sorption capacity (Renman & Renman 2010; Bus & Karczmarczyk 2014). The material is of natural origin, made from the calciferous bedrock opoka by heating at high temperature to transform calcium to the CaO form. In this study, material with grains of 2–5 mm was used. Characteristics of the reactive material are set out in Table 1.

**RESULTS AND DISCUSSION**

**Leakage quantity and quality**

A column experiment was performed for extensive substrate underlined with Polonite® layer (SP) and the same substrate without a supporting layer as a reference (S). Reduction of
the effluent volumes from both the S and SP experiments was observed (Figures 2 and 3). The average effluent from S and SP experiments was 61.1 mL (5.8–543.3 mL) and 46.4 mL (3.3–473.3 mL) when the average irrigation rate was 175.5 mL (6.3–758.0 mL).

The tap water used for irrigation was free of phosphorus, apart from one irrigation event (day 79, 0.004 mg·L⁻¹/C₀) (Figure 2). For 23 simulated rain events, only seven leakages occurred in the case of the SP experiment, of which only two were polluted by phosphorus (0.003 and 0.004 mg·L⁻¹). On day 79, P was indicated in both tap water used for rainfall simulation (0.004 mg P-PO₄/L) and leakage from the SP (0.004 mg P-PO₄/L) experiment. Similar concentrations in rainfall and leachate in the SP may be treated as accidental. For the S experiment, 12 leakages occurred, and all of them were polluted by phosphorus (Figure 2). The average P-PO₄ concentration of the column experiment underlined by Polonite® was 0.001 mg/L (0.000–0.004 mg·L⁻¹) and the concentration of the reference S experiment was 0.025 mg/L (0.001–0.082 mg·L⁻¹). A limited number of leakages in the SP experiment is the result of high water adsorption of used reactive material (Table 1). Both SP leachates containing phosphorus, observed on days 28 and 79, appeared after long periods without rainfall simulation (12 and 10 days, respectively) as a result of high irrigation and high substrate moisture.

As a result of the column experiment performed with green roof substrate underlined by Polonite®, it can be stated that implemented reactive material is very efficient in terms of reducing P leaching and increasing substrate retention ability (Figures 3 and 4). The presence of a 2 cm layer of the reactive material Polonite® reduces the P-PO₄ average runoff concentration by 25 times compared with substrate runoff. The average retention ability of S and SP experiments was 65% and 74%, respectively. Similar retention was obtained by Li & Babcock (2014) based on laboratory experiments and field measurements; they reduced stormwater runoff volume by 30 to 86%.

Previously, Polonite® was successfully used for reduction of phosphorus concentration from wastewater (Renman & Renman 2010) and surface water (Karczmarczyk et al. 2016). The average phosphorus reduction in the case of wastewater ranged from 81.0 to 91.0% (Renman & Renman 2010) and from 18.0 to 34.6% for artificial surface water (Karczmarczyk et al. 2016). This study shows that it is also a potential material for upgrading the green roof technology to limit the phosphorus concentration in runoff.

Using Polonite® as a P-reactive drainage layer may have potential limitations. A previous study reported alkaline pH, which increased to 11.8 and 12.5 after Polonite® treatment (Renman & Renman 2010). An important issue is also the density of material used. Too heavy materials may affect the construction of the roof. Application of Polonite® as an additional layer will also increase the total cost of investment.

**Green roof runoff comparison**

Previous studies showed that runoff from green roofs can be polluted with phosphorus. Moran et al. (2005) obtained concentrations in the outflow ranging from 0.6 to 1.5 mg·L⁻¹. Aitkenhead-Peterson et al. (2011) got a runoff phosphorus concentration between 0.27 and 0.37 mg·P·L⁻¹ from a roof with vegetation cover and 0.4 mg·P·L⁻¹ from a roof without vegetation. Burszta-Adamiak (2014) observed the concentration ranging from 2.35 to 3.58 mg·P·PO₄·L⁻¹ in green roof runoff. The reason for high P concentration is probably compost reaching the substrate and periodic fertilization. Also, other fertilized green roofs tend to have runoff with higher P concentrations, e.g. 0.3–0.7 mg·P·L⁻¹ and
Figure 2 | Irrigation rate, leakage of S and SP experiments with P-PO$_4$ concentration. Note: scales on concentration axis are different.
0.9–1.6 mg P L\(^{-1}\) for extensive green roofs located in Sweden (Czemiel Berndtsson et al. 2006). On the contrary, even fertilized green roofs are able to emit lower P concentration runoff (0.003–0.079 mg P L\(^{-1}\)) (Gregoire & Clausen 2014). However, the runoff from roofs without fertilization is characterized by low P concentration (0.01 mgP·L\(^{-1}\) reported by Czemiel Berndtsson et al. 2009) or even lack of phosphorus (Czemiel Berndtsson et al. 2006).

The presence of a P reactive layer influences the P concentration in green roof runoff, although the Polonite\(^{®}\) previously used as a P reactive material for water and wastewater treatment (Klimeski et al. 2012) seems to be efficient in green roof runoff treatment in which concentrations of P are low. In another study, a 2 cm layer of autoclaved aerated concrete (AAC) underlying extensive green roof substrate reduced the P-PO\(_4\) concentration to less than 0.05 mg L\(^{-1}\) (Karczmarczyk et al. 2014). By underlying the substrate with AAC, P concentration was reduced by 60%. In the present study with Polonite\(^{®}\), the P reduction equals 96%. Also, the addition of lightweight aggregates to the substrate may influence decreasing P concentration in runoff. Teemusk & Mander (2007) obtained a P concentration in runoff ranging from 0.011 to 0.056 mg P-PO\(_4\)·L\(^{-1}\).

Although the leachate concentrations of phosphorus presented above are not high, it should be remembered that they still may be the source of phosphorus in water discharged from the green roofs to receivers. Keeping in mind that green roofs are a technology implemented in urban landscapes, the most popular type of runoff receivers are ponds retaining the water from residential areas. The stagnant water condition makes this reservoir P-sensitive, which can promote implementation of P-reactive drainage in the green roof construction in the future.

**CONCLUSIONS**

The present study investigated the phosphorus concentration in runoff from green roof substrate and its ability to retain water based on simulated rain events. The P concentration of runoff from green roof substrate and substrate underlying by the reactive material Polonite\(^{®}\) was examined. In the case of extensive substrate use, the potential sources of phosphorus in outflow are the peat and compost components, which are washed out during simulated rain events. The substrate used in our research contains organic matter up to 60 kg/m\(^3\) (product information). Results revealed that the presence of a Polonite\(^{®}\) layer under the substrate showed potential for decreasing P-PO\(_4\) concentration in runoff. The leakage phosphorus concentration ranged from 0.001 to 0.082 mgP-PO\(_4\)·L\(^{-1}\), with an average value of 0.025 mgP-PO\(_4\)·L\(^{-1}\) in the S experiment and 0.000–0.004 mgP-PO\(_4\)·L\(^{-1}\) and 0.001 mgP-PO\(_4\)·L\(^{-1}\) in the SP experiment, respectively. The 2 cm layer of Polonite\(^{®}\) was efficient in reducing P outflow from green roof substrate by 96%. Similarly, volumes of leakage from both experiments were reduced. The average retention ability was 65% and 74% for the S and the SP experiment, respectively. Thus, green roofs with a reactive material layer, implemented in urban areas for rain water retention and delaying runoff, are also effective for protection of water quality.
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