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Article

Effect of P-Reactive Drainage Aggregates on Green Roof Runoff Quality

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Abstract: The main hypothesis of the presented study is that the negative effect of phosphorus leaching from a green roof substrate can be reduced by including P-reactive material in a drainage layer. In this work, different aggregates (Pollytag®, lightweight expanded clay aggregates, chalcedony, serpentynite and crushed autoclaved aerated concrete) to be used as the green roof drainage layer are described. Physical parameters, e.g., granulometric composition, water absorption, bulk density and porosity are assessed. A phosphorus sorption isotherm and a kinetic test were performed. Physical and chemical characteristics of the materials were used as a base for choosing the best media for the drainage layer. The P-removal efficiency of crushed autoclaved aerated concrete was confirmed in a column experiment. Adding the implementation of the P-reactive material in a drainage layer during construction can reduce the negative effect of substrate on green roof runoff quality.

Keywords: phosphorus; green roof; substrate; aggregates; Pollytag®; LECA; chalcedony; serpentinite; AAC

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1. Introduction

Green roofs are a method of recovering green space in urban areas. They are engineered constructions consisting of different layers: hydroisolation, drainage, geomembrane, substrate and plant cover. Two of them, the substrate and the drainage layer, can bring or solve environmental problems, depending on the type of materials used in their construction.

Czemiel Berndtsson [1] summarized potential factors influencing the quality of green roof runoff. The most important are the type and composition of soil or artificial plant growth medium (substrate), the thickness of the substrate layer, the drainage type, the material used, the roof age and the roof maintenance (fertilization). The materials used in the green roof construction can be a source of contaminants in runoff. Moulineux *et al.* [2] characterized alternative materials which could be used in the construction of the substrate layer. In the leachate from tested materials (crushed brick, pellets made from clay, sewage sludge and paper ash) they found some micro and macro pollutants such as aluminum, calcium, magnesium, potassium, sodium, strontium, titanium and zinc. Leaching of metals (Zn, Cd, Pb) from green roofs filled with the pine bark mixture was also observed by Aslup *et al.* [3]. Copper was also found in the runoff samples from a green roof by Gregoire and Clausen [4]. Zinc was present in the leachate from a medium made from recycled crumb rubber [5]. Gnecco *et al.* [6] showed that the green roof behaves as a source of solids, COD and potassium, while zinc and copper are retained in the system. Green roof runoff can contain increased levels of nutrients and total suspended solids compared to the source of water creating runoff [7,8].

Phosphates are listed in Water Framework Directive (60/2000/EC Annex VIII) as a substance which contributes to eutrophication [9]. Surplus of phosphorous in natural or artificial water bodies may lead to water quality deterioration that makes it unsuitable for agricultural, economic or recreational use. Table 1 presents the limit values of phosphates for the eutrophication process. Addition of 1 g of P promotes the growth of up to 100 g of algae that represents the principal trigger of the eutrophication and toxic blue-green algae blooms in the surface water [10]. Even the concentration above 0.020 mg PO_4-P·L^{-1} may affect the trophy of water ecosystem. Some authors recommended phosphates limits for controlling the nuisance caused by riverine algae at the level of 0.015 mg PO_4-P·L^{-1} [11] or even 0.006 mg PO_4-P·L^{-1} [12].

Table 1. The examples of P limit values of eutrophication process.

State Assessment System of Water Quality	*P* concentration (mg PO_4-P·L^{-1})	References
OECD	0.035	[13]
New Hapshire, USA	0.020	[14]
Canada	0.035	[15]
Waikato region, New Zealand	0.020	[16]

Green roofs can be a source of the phosphorus in runoff (e.g., [17,18]). Concentrations of phosphorus and phosphates found in green roof runoff in different studies are presented in Table 2. The main source of the P-leaching is a plant substrate and the factors influencing the load of phosphorus in runoff include: plants, roof age and roof maintenance [17,19]. The substrate is an artificial medium which substitutes natural soil for plant growth. It usually consists of a mixture of mineral (e.g., sand, gravel aggregate, debris) and organic particles (e.g., bark, peat, compost). The share of compost in substrate mass can vary from few to several dozen percent, although a big share of compost can cause negative effect such as decomposition of organic material and self-consolidation of soil [19,20]. The percentage of compost in the soil media and the fertilizer used are the two components apparently contributing to nutrients in runoff [1,4].

Properly chosen green roof media are fundamental for roof hydraulic dynamics and for providing optimal plant growth conditions [5]. Substrate material (depth and physical properties, particularly water holding capacity) is essential for the survival of plants, especially in hot and dry climates [21,22]. Beck *et al.* [7] stated that there is a need to find a balance between providing sufficient nutrients for plant growth and simultaneously reducing the leaching of nutrients in the runoff. One of the solutions is to use a soil amendment which is able to decrease the concentrations of released phosphate from the substrate [7]. The alternative option is to underline the substrate with P-reactive material.

The primary function of a drainage layer is to remove the excess of rain water which may cause root decay. The role of drainage material is also to store some amount of water and retain it for a dry period. Drainage materials used in green roofs include: natural materials, recycled materials, manufactured drainage mats and aggregates (Table 3). Some of them can also be reactive to phosphorus.

The drainage layer should be light and thin; thus, materials such as polyethylene and polypropylene are preferred when building green roofs due to weight limitations, flexibility to transport in rolls, easy installation, high strength, durability and a low production cost [23]. However, production of polymers has high environmental impact, with the release of the carbon dioxide of 2 kg per 1 kg of LDPE and 1.7 kg per 1 kg of PP. It is also characterized by a considerably high amount of material and energy use [23]. It is essential to explore materials that can replace the current use of polymers to enhance overall sustainability of green roofs. Natural and commercially available aggregates have great potential on the green roof market. As they can be locally sourced they are more economically and environmentally acceptable.

Looking for alternative materials for green roof construction focuses mostly on the materials with low environmental impact, e.g., recycled materials [2,5,23]. To date, little research has been done to optimize the drainage layer of a green roof to be effective in hydraulic properties as well as runoff quality. This paper describes an experiment that determines physical and chemical properties of aggregates to be used in the drainage layer of green roofs with the focus on their phosphorus sorption capacity. The performed experiment has following objectives: (I) to assess physical properties of aggregates as a base of their implementation in green roof construction; (II) to assess phosphorus sorption capacity of tested aggregates; and (III) to check the efficiency of an aggregate as a trap for phosphorus released from the substrate.

Table 2. Phosphorus found in runoff from green roofs—literature review.

Type Of Green Roof	**Location**	**Soil Substrate**	**Drainage Type**	**Roof Age [years]**	**Maitenance**	**P Concentration in Runoff**	**References**
Extensive, *Sedum* plants	Malmö, Sweden	Crushed lava, natural calcareous soil, clay and shredded peat	Crushed brick	1–2	Fertilized	0.25–0.28 mg PO_4-P·L^{-1} 0.2–0.3 mg P·L^{-1}	[24]
Extensive, *Sedum* plants	Malmö, Sweden	Crushed lava, natural calcareous soil, clay and shredded peat	Shingle (4–8 mm, gneiss-granite origin)	1–2	Fertilized	0.25–0.35 mg PO_4-P·L^{-1} 0.3–0.7 mg P·L^{-1}	[24]
Extensive, *Sedum* plants	Malmö, Sweden	Crushed lava, natural calcareous soil, clay and shredded peat	Shingle (4–8 mm, gneiss-granite origin)	9	Non fertilized	No P release	[24]
Extensive, *Sedum* plants	Lund, Sweden	Crushed lava, natural calcareous soil, clay and shredded peat	Flor-Depot drainage (thickness of 3.5 mm)	1–2	Fertilized	0.8–1.4 mg PO_4-P·L^{-1} 0.9–1.6 mg P·L^{-1}	[24]
Exstensive, herbaceous and *Sedum* species	Taipei, Taiwan	Sandy loam/expanded clay/vermiculite/waste cotton 2:3:3:1:1	–	3	Irregular weeding and fertilization	0.15 mgP·L^{-1}	[25]
Intensive, leave trees and bushes	Fukuoka, Japan	Aquasoil (inorganic lightweight soil made from perlite)	Plastic	12	–	0 mg PO_4-P·L^{-1} 0.01 mg P·L^{-1}	[17]
Extensive, *Sedum* plants	Malmö, Sweden	Crushed lava, natural calcareous soil, clay and shredded peat	Shingle (coarse gravel)	4	Fertilized during first 2 years of operation	0.27 mg PO_4-P·L^{-1} 0.31 mg P·L^{-1}	[17]
Extensive, *Sedum* plants	Storrs, United States	75% lightweight expanded shale, 15% composted biosolids, 10% perlite	GreenGrid modules	1–2	Fertilized	0.003–0.079 mg PO_4-P·L^{-1} 0.018–0.096 mg P·L^{-1}	[4]
Extensive, *Sedum* plants	Goldsboro, United States	55% Perma Till, 30% Sand, 15% composted cow manure	Hydrodrain 300	1	–	0.6–1.4 mg P·L^{-1}	[26]
Extensive, *Sedum* plants	Tartu, Estonia	66% LWA, 30% humus, 4% clay	Plastic wave and rock wool	1–6	–	0.23 mg PO_4-P·L^{-1} 0.27 mg P·L^{-1}	[18,27]
Extensive, sod roof	Talinn, Estonia	Biolan black soil (horticultural peat, composted soil mix, sand, composted chicken dung, dolomite lime)	Plastic wave drainage	2–5	–	0.18 mg PO_4-P·L^{-1} 0.24 mg P·L^{-1}	[27]
Extensive, *S. kamtschaticum*, *D. cooperi*, *T. calycinum*	Texas, United States	Rooflite drain	TectaGreen modules	1	irrigated	0.27–0.37 mg PO_4-P·L^{-1}	[28]

Table 3. Types and examples of drainage materials for green roofs.

Natural Materials	Recycled Materials	Manufactured Drainage Mats	Manufactured Aggregates
Gravel	Crushed brick	Plastic sheets with cups	LECA
Crushed rock	Shredded tires	Foam materials	Pollytag®
Crushed lava, *etc.*	Tumbled glass, *etc.*	Rockwool, *etc.*	Slag, *etc.*

2. Materials and Methods

Different materials (aggregates), typically used for drainage layer construction, and some alternative P-reactive materials were tested as a potential drainage medium as well as a P-trap. Materials used in the study were Pollytag®, LECA (lightweight expanded clay aggregate), chalcedony, serpentynite and AAC (autoclaved aerated concrete) (Figure 1). Pollytag®, LECA, chalcedony and serpentynite, as well as the substrate, were supplied by a local green roof company; AAC is an alternative material which was tested before in the Laboratory of Ecotechnology Water Center SGGW for phosphorus removal from surface water [29–31].

Figure 1. Drainage materials tested in the study, from the left: Pollytag®, lightweight expanded clay aggregate (LECA), chalcedony, serpentynite and autoclaved aerated concrete (AAC).

2.1. Tested Materials

Pollytag®. Lightweight aggregate Pollytag® is a commercial product. Pollytag® is manufactured of fly ashes from a thermal-electric power station. The main compounds are SiO_2 (58%), Al_2O_3 (22%), CaO (2.2%) and MgO (1.4%). Aggregates are used in different types of construction. Quick absorption features of a dry aggregate are used in gardening where Pollytag® is a retention layer regulating the quantity of water necessary for right vegetation. Of a similar importance are pavements made of Pollytag® in parks, tennis courts, playing fields, *etc.* [32] *LECA.* Light expanded clay aggregate consists of small, lightweight, bloated particles of burnt clay. Light expanded clay aggregate is produced in more than 20 countries with different brands name. The main compounds are SiO_2 (54%), Fe_2O_3 (14%), Al_2O_3 (12%), MgO (2%), CaO (0.6%). LECA is used in many applications. As LECA is light and easy applied it is a proper construction material for flooring and roofing. Other applications are: bio-filtration (wastewater treatment) and agriculture [33].

Chalcedony. Chalcedony forms from watery silica gels at relatively low temperatures. Chalcedony can be found in weathering volcanic rocks, but also in sedimentary ones. Chalcedony may have a variety of applications including construction and water filtration.

Serpentinite. Serpentinite is a metamorphic rock. It consists predominantly of magnesium silicate and iron oxide minerals. Serpentinite has been widely used in monuments and it is very popular in civil construction nowadays. As it has a beautiful green color when wet, it is widely used as a decorative material in garden ponds.

AAC. Autoclaved aerated concrete is a lightweight popular construction material. Quartz sand, lime or cement and water are used as a binding agent. The material structure of aerated concrete is characterized by its porosity and low density. The main compounds are SiO_2 (57%), CaO (25%), Al_2O_3 (2%), SO_3 (1.3%), Fe_2O_3 (1%) and MgO (0.5%). In this study, mechanically crashed material was used.

2.2. Assessment of Physical Properties

To assess the availability of aggregate to be used in construction of green roof, some of the following properties should be taken into account: granulometric composition, frost resistance, water permeability and water storage capacity, structure and layer stability, behavior under compressive loads, pH value and salt content [34]. Determination of physical properties of aggregates was carried out in accordance with the following standards: granulometric composition PN EN 933-1:2012, water absorption PN EN 1097-6:2002, bulk density PN EN 1097-3:2002 and porosity PN-EN 1936:2001 (Table 4).

Table 4. Summary table of performed tests.

Material	Physical Parameters					Chemical Parameters			Column Experiment
	Grain Size	Porocity	Bulk Density	Moisture	Water Adsorption	Preliminary Sorption Test	Sorption Izoterm	Sorption Kinetic	
Pollytag®	√	√	√	√	√	√	–	–	–
LECA	√	√	√	√	√	√	–	–	–
Chalcedony	√	√	√	√	√	√	–	–	–
Serpentinite	√	√	√	√	√	√	–	–	–
AAC	√	√	√	√	√	√	√	√	√

Notes: LECA—light expanded clay aggregates; AAC—autoclaved aerated concrete; √—test performed.

2.3. Assessment of P-Retention Capacity and Kinetics

Phosphorus sorption capacity of the tested aggregates was assessed in two stages: preliminary test (qualitative) and the main test (sorption isotherm and kinetics) (Table 4). A qualitative test was performed for all tested aggregates by short (15 min) mixing of triplicate 1 g samples of the material (5 g in case of LECA and serpentinite) with a P solution prepared from KH_2PO_4 in concentration from 1 to 50 $mg \cdot L^{-1}$.

Main sorption isotherm and kinetic tests were performed only for AAC, as it got the best result from the preliminary test.

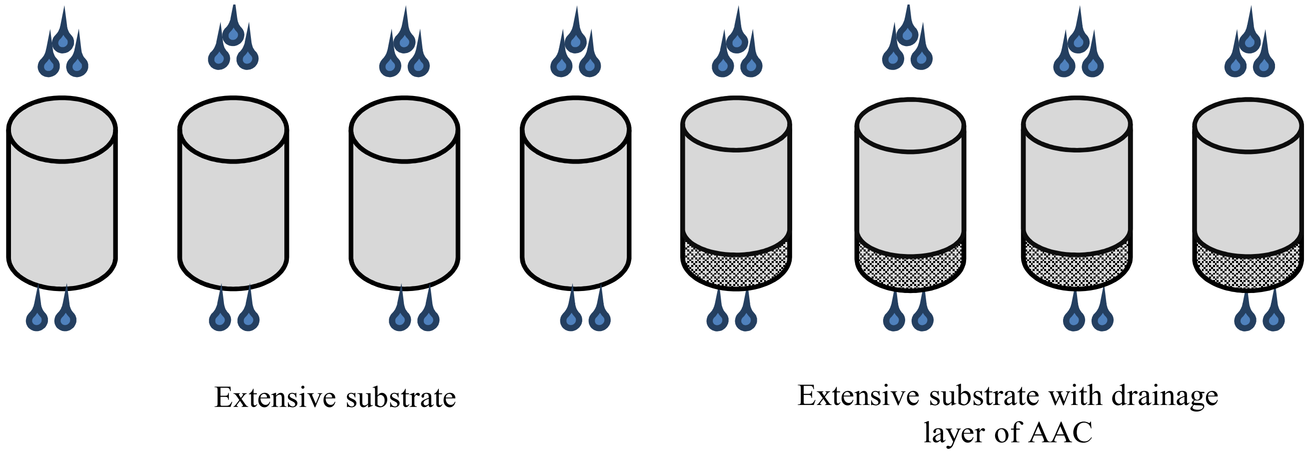
A phosphorus sorption batch test was performed for AAC by long (24 h) mixing of 1 g of the material (triplicate) with the P-solution in increasing concentrations from 1 to 1000 $mg \cdot L^{-1}$. P-sorption was calculated based on the difference of load of P added and obtained in a filtered sample. A linear form of Laungmuir isotherm ($1/q_s = 1/C_s \cdot 1/K_L + a_L/k_L$) was used to assess the apparent P-sorption capacity [35]. Parameters K_L (reflects the solute adsorptivity) and a_L (related to the energy of adsorption) are Langmuir constants, whereas and K_L/a_L ratio is defined as adsorption capacity.

A batch sorption kinetic test was performed for AAC for initial P concentrations of 0.25, 0.56 and 1.0 $mg \cdot L^{-1}$, by increasing the contact time from 5 min to 48 h. Low concentrations of P in the kinetic test were chosen based on literature review of P concentrations in leachate from green roof substrates (see Table 2).

2.4. Column Experiment

Column experiment was performed to prove the efficiency of AAC as a supporting material for limiting P leaching from extensive green roof substrate. Four columns with a diameter of 14.5 cm were filled with 10 cm of extensive green roof substrate underlined by 2 cm of drainage layer made from AAC (Figure 2). Columns were periodically irrigated with tap water to simulate rain event. Leachate from each column was sampled and analyzed for P-PO_4 concentration, by flow injection analysis using FIA-Star. Results were compared with the concentration of phosphorus in leachate from the substrate without supporting drainage layer, described by [8]. Both experiments were carried out for 80 days.

Figure 2. Set up of column experiment.



3. Results and Discussion

3.1. Physical Properties of Aggregates

The greatest weight from tested aggregates characterizes serpentinite, while the lowest for AAC (Table 5). All aggregates can be classified as lightweight (bulk density of 1200 kg m^{-3}). Bulk density of aggregates is very important in case of green roofs as it influences the weight of the drainage layer.

Table 5. Summary table of physical parameters of aggregates.

Material	Grain Size (mm)	Porosity (%)	Bulk Density (kg·m^{-3})	Moisture (%)	Water Adsorption (%)
Pollytag®	8–11	62.32	660	0.51	29.60
LECA	8–16	52.20	950	2.64	14.60
Chalcedony	1–9	54.55	1110	0.20	20.11
Serpentinite	6–17	52.67	1240	0.33	7.60
AAC	1–6	83.75	300	6.05	83.74

Porosity of materials determines such characteristics as: aggregate strength, abrasion resistance, specific gravity, thermal insulation, binding capacity, and resistance to freezing and thawing, and frost resistance. Assessed porosity amounted from 52.20% for the LECA to 83.75% for the AAC (Table 4).

High porosity minimizes water absorption properties and promotes infiltration [36]. Porosity is an important parameter of the green roof drainage layer as it determines the space for roots penetration and the amount of retained water.

The highest water absorption was observed in AAC (83.74%), the lowest in serpentinite (7.60%). Typically, the absorption of construction materials is lower than the porosity. This is due to the fact that water is not able to get into the closed pores and, in the case of large pores, does not fill them, but only wets the walls. Such observation was made for four tested aggregates, but not for AAC. Porous structure of AAC can absorb up to 100% of water and even more [37]. This phenomenon has been explained by Ioannu *et al.* [38] as a result of structural aspects of partitions between pores.

Moisture of aggregate depends on its sorption properties (structure of the material, temperature and humidity). In case of the implementation of aggregate in the construction of green roof drainage layer, it is exposed to high moisture which can contribute to the deterioration of its physical and mechanical properties and promotes the development of micro-organisms (e.g., lower heat-insulating properties and strength).The highest moisture was observed in AAC (6.05%) and LECA (2.64%). Other aggregates had a moisture content below 1%. Moisture of the aggregates strongly influences thermal conductivity of the material which substantially increases with increasing humidity. Therefore, AAC and LECA are aggregates of high thermal conductivity. Water transport phenomena in porous materials is a very complicated process, because, in addition to the molecular flow, surface diffusion, capillary transportation and other forms of transportation may occur [39]. At the same time, sorption and desorption processes, phase transitions, and thermo-diffusion may take place. All these processes depend on the pore structure of the material and its thermal and moisture properties [40].

3.2. P-Retention Capacity of Aggregates

Four out of five tested aggregates (Pollytag®, LECA, chalcedony and serpentynite) are often used as construction material in green roof systems. The goal of the study was to assess if they can also work as a trap for phosphorus leaching from green roof substrate. Preliminary test showed that three of the tested aggregates (LECA, chalcedony and serpentinite) are not reactive to phosphorus (Table 6). In case of chalcedony and serpentenite the result was predictable as they are not rich in Ca, Al or Fe groups. But, it can be a little surprising in case of LECA which was tested before as a reactive material to phosphorus in wastewater treatment [41,42]. However, it is also known that LECA is a product made from clay and its properties depend on the raw material. The highest P removal ability is described for LECA from Norway [43].

Table 6. Results of the preliminary sorption test.

Initial P Concentration ($mg \cdot L^{-1}$)	Sorption of P (mg $P\text{-}PO_4$ Per 1 g of Material)				
	Pollytag®	LECA	Chalcedony	Serpentinite	AAC
1	0	0	0	0	0.03
2	0	0	0	0	0.05
5	–	–	–	–	0.18
10	0.34	0	0	0	0.53
20	0.89	0	0	0	0.26
50	2.67	0	0	0	0.35

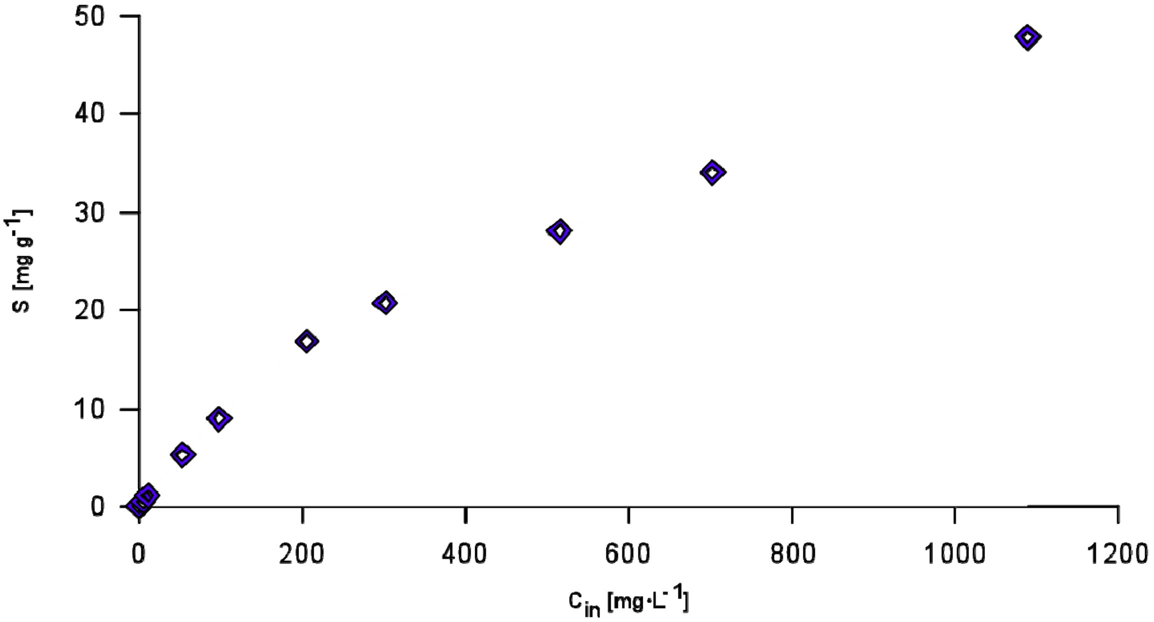
Pollytag® and AAC both gave positive result from the preliminary sorption test. Pollytag®, as a product manufactured from fly ash, has potential to be reactive to phosphorus, however AAC was more active in low P concentrations. In case of leachate from green roof substrate we may expect P-PO_4 concentrations of about 0.1 mg·L^{-1} [8]. Therefore, more detailed P sorption tests were performed for AAC.

3.3. Phosphorus Sorption by AAC

Autoclaved aerated concrete is a lightweight material widely used in construction. It is also known as a reactive material to phosphorus removal [44]. The main advantage of the material is that it is manufactured, so that homogenous, and its properties are stable. For green roofs drainage it can be used as manufactured but also as a recycled product (after demolition of a building). In both cases, AAC has to be crushed to be used as a reactive material.

A sorption experiment (Figure 3) was done for long contact time (24 h), which is realistic in natural conditions. Between rain events, rainwater can be stored in drainage layer even longer. However, if the rain is intensive, the excess of water will just flow the drainage layer and go directly to the receiver. Apparent P sorption capacity for AAC obtained from the batch sorption experiment, based on K_L/a_L ratio, amounts to 78.8 mg·g^{-1}. This is a high value and can be compared with other P reactive materials used in wastewater treatment [45]. High P sorption capacity makes AAC potentially attractive material supporting green roof substrate. Low P concentration in leachate and high P sorption ability provide efficient and long life protection of stormwater receivers.

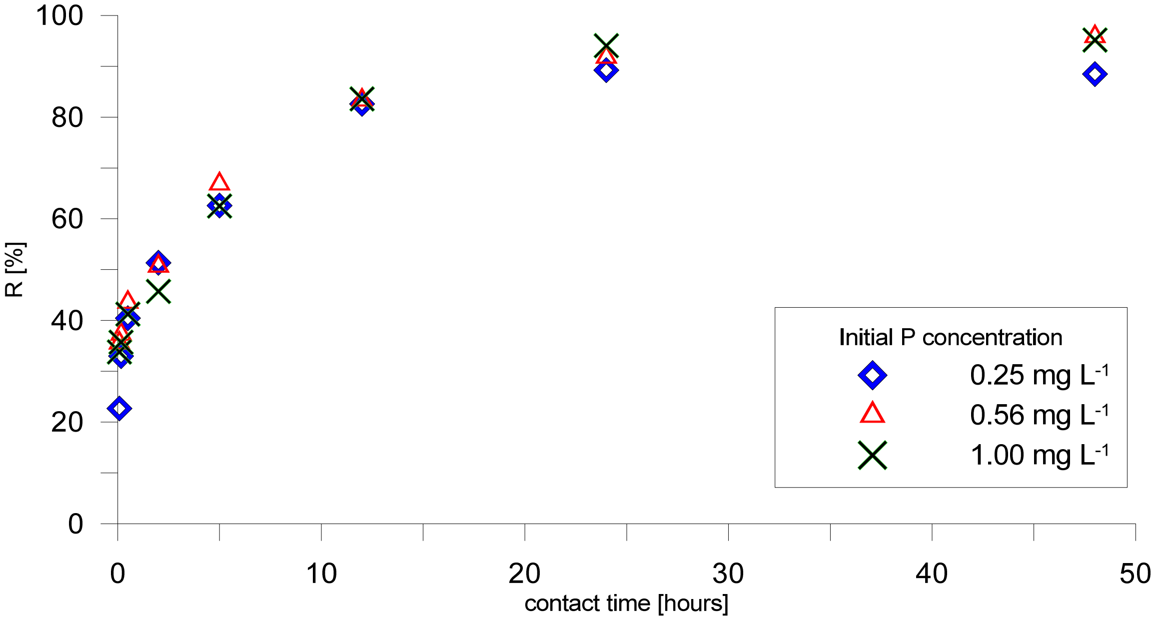
Figure 3. Phosphorus sorption isotherm for AAC.



To be effective for P removal in different conditions, retention time necessary to retain phosphorus should be as short as possible. That is why a kinetics test is very important. AAC appeared to be very active for phosphorus. High reduction of 70% of P was observed within retention time of 10 h with over

20% in the first 5 min (Figure 4). With P concentrations ranging from 0.25 mg·L^{-1} to 1 mg·L^{-1}, P sorption rate proved to be independent of the initial concentration.

Figure 4. P sorption kinetic for different initial P concentrations.



3.4. Column Study

A column experiment was performed for extensive green roof substrate underlined by AAC layer. The results of previous study, performed with the same substrate but without supporting layer, were used as a reference. In the mentioned study, leaching of phosphorus from substrate was observed, as a result of rain simulation, with average concentration of 0.13 mg P-PO$_4$·L^{-1} (Figure 5). Concentration of P in leachate was higher in the first phase of the experiment, later stabilizing at the level of 0.08 mg P-PO$_4$·L^{-1} [8].

As a result of the performed column experiment with green roof substrate underlined with AAC, it can be stated that used aggregates are very efficient in terms of reduction of leaching P (Figure 6). Phosphorus occurred in leachate incidentally and in very low concentrations (less than 0.05 mg·L^{-1}). For thirteen simulated rain events only six leechates occurred, out of which only three were polluted with phosphorus (Figure 5). A limited number of leachates is a result of high water absorption of AAC. In a technical scale, drainage layer from AAC can increase the delay of rainwater runoff as an additional benefit. Green roof substrate can release from 1.0 to 2.0 mg P-PO$_4$·kg^{-1} [4]. In case of the tested substrate it was estimated at 1.9 mg P-PO$_4$·kg^{-1} (the first phase of the experiment) to 1.1 mg P-PO$_4$·kg^{-1} [8]. Comparing to the previous result, by underlying the green roof substrate with reactive material (AAC), a leveling of P load in mass of about 1 kg·ha^{-1} could be obtained.

Figure 5. Irrigation rate, leachate occurrence and P-PO$_4$ concentration in leachate from the substrate of extensive green roof substrate—reference level for column experiment, based on [8].

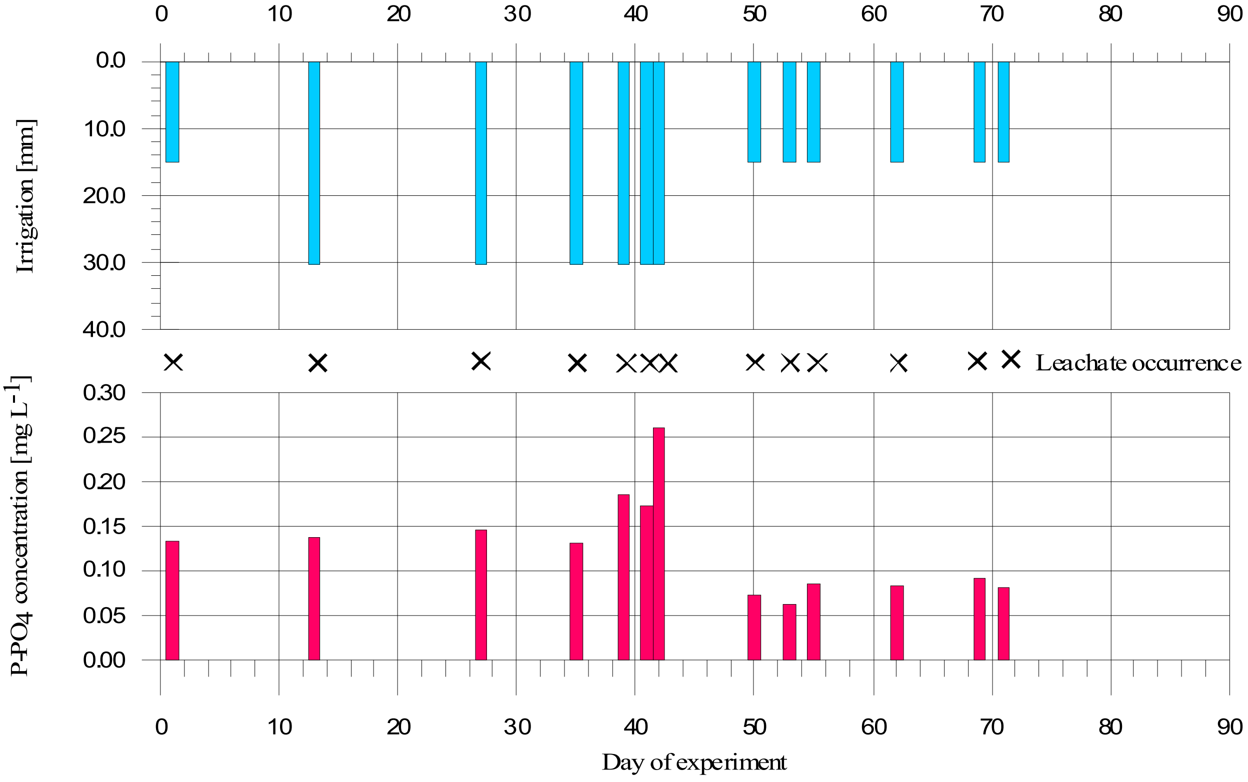
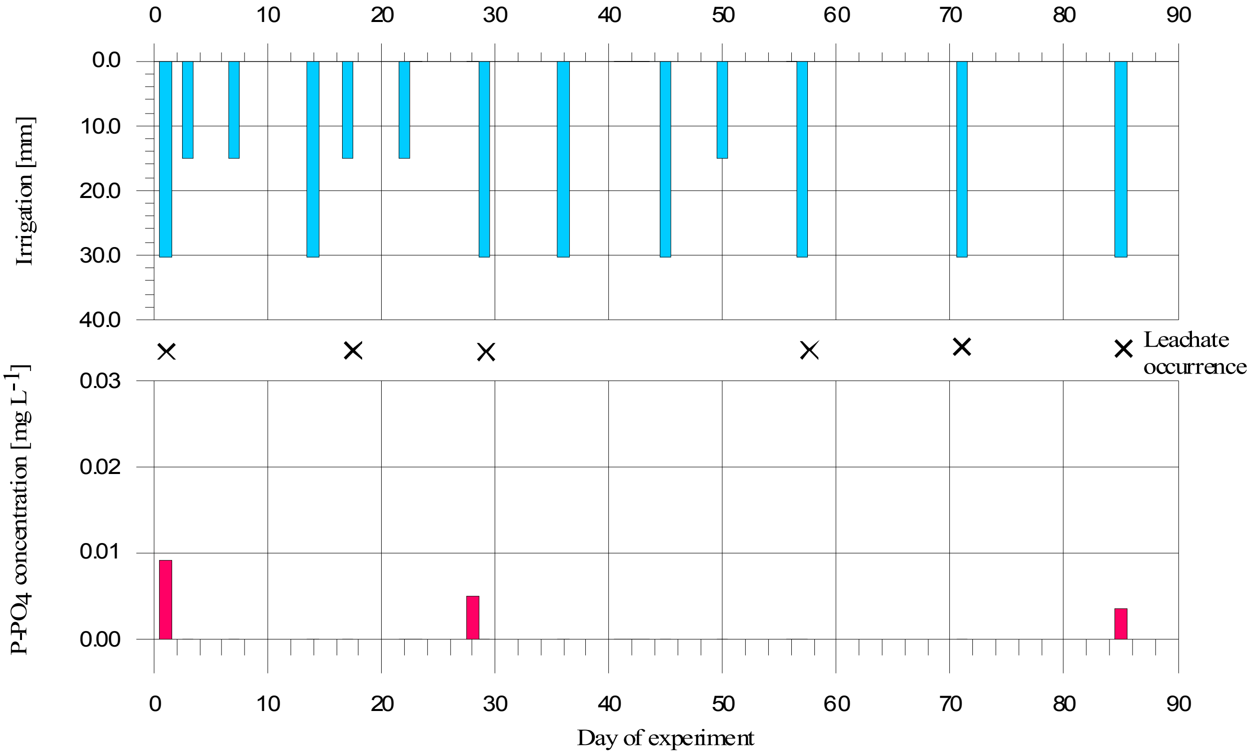


Figure 6. Irrigation rate, leachate occurrence and P-PO$_4$ concentration in leachate from substrate of extensive green roof underlined with drainage layer made of AAC—result from column experiment (note: vertical scale of Figures 4 and 5 are different).



4. Conclusions

A holistic approach to the environmental problem requires a solution without creating other problems. Thus, green roofs implemented in urban areas for increasing rain water retention and delaying runoff, should also work for protection of water quality. Eutrophication of water bodies is one of the most important environmental problems of the 21st century. It results in lowering quality of water resources, social and economical loses. Recent studies have been focused on improving wastewater treatment efficiency and limitation of agricultural runoff. It is also very important to focus on other phosphorus sources in lakes and rivers. Previous research showed that improperly constructed and maintained green roofs can be a source of phosphorus. The main P sources are substrate and fertilization of cultivated plants.

Materials tested in the study were chosen on the basis of their price and availability. Four of them (apart from AAC) are used in green roof constructions in Poland. Some of them, e.g., serpentinite and Pollytag® may also release less desirable elements (e.g., asbestos, heavy metals). This was not considered in the study; however, a potential environmental risk should be taken into account in case of implementation. Out of the four materials only Pollytag® seems to have a potential to be effective for P removal, but it was no active in low P concentrations. The use of Pollytag® as a P sorbent can be considered in case of sewage or highly polluted waters.

Physical parameters of AAC make it suitable for implementation as a drainage material in green roof system. High water absorption of aggregates decreases the volume of leaching water. It can result in the delay of roof runoff as an additional benefit. The possible negative impact of AAC on water environment may be the release of SO_4^{2-} ions as a result of the dissolution of the anhydrite. Also trace concentrations of metals can be found in leachate. However, high P-removal capacity and its efficiency in low phosphorus concentrations, as well as short sorption time, make it attractive from the point of view of runoff quality. The use of crushed AAC from the demolition of buildings will support the sustainability of the green roof system.

Author Contributions

Agnieszka Karczmarczyk contributed to Study conception and design; Performance of the experiment: physical properties: Anna Baryła; Isoterm and kinetic tests: Agnieszka Bus; Column study: Agnieszka Karczmarczyk, Agnieszka Bus; Analysis and interpretation of data: Agnieszka Karczmarczyk, Anna Baryła, Agnieszka Bus; Drafting of manuscript: Agnieszka Karczmarczyk, Anna Baryła; Critical revision: Agnieszka Karczmarczyk, Anna Baryła, Agnieszka Bus.

Conflicts of Interest

The authors declare no conflict of interest.

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