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Role of drainage layer on green roofs in limiting the runoff of rainwater from urbanized areas

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Abstract

Green roofs play a significant role in sustainable drainage systems. They form absorbent surfaces for rainwater, which they retain with the aid of profile and plants. Such roofs therefore take an active part in improving the climatic conditions of a city and, more broadly, the water balance of urbanized areas. One of the factors influencing the hydrological efficiency of green roofs is the drainage layer. In the article, column studies were carried out under field conditions involving the comparison of the retention abilities of two aggregates serving as the drainage layer of green roofs, i.e. Leca[®] and quartzite grit. The average retention of the substrate was 48%; for a 5 cm drainage layer of Leca[®] retention was 57%, for a 10 cm layer of Leca average retention was 61%. For a 5 cm layer of quartzite grit average retention was 50%, for 10 cm layer of quartzite grit 53%. The highest retention was obtained for the column with the substrate and 10-centimeter layer of Leca[®]. At the same time, it was shown that Leca[®] is a better retention material than quartzite grit. The initial state of substrate moisture content from a green roof appears to be a significant factor in reducing rainfall runoff from a green roof; the obtained values of initial moisture content made for a higher correlation than the antecedent dry weather period.

Key words: *drainage layer, green roof, retention, runoff, substrates*

INTRODUCTION

The progressing development of cities is changing natural areas into impermeable surfaces, leading to a change in the hydrological cycle [ATALLAH *et al.* 2018; BARSZCZ 2016; BERNDTSSON 2010; MROWIEC, SOB CZYK 2014; ROMANIAK 2017]. Moreover, the aging infrastructure in cities, urbanization rate and climate change, by the degraded hydrological cycle, may constitute a threat to urban drainage. Sustainable urban drainage systems constructed in the USA, Germany, Netherlands [BOAS BERG *et al.* 2017; KOHLER 2006; PALLA *et al.* 2010; WONG, JIM 2015], may serve as alternative strategies for urban planning and rainwater management in urbanized areas [BARYŁA *et al.* 2018a; STOVIN *et al.* 2012; SZULCZEWSKA *et al.* 2014]. These systems copy the relationships taking place between a natural catchment, returning the imbalanced proportions between the processes of retention, infil-

tration, transpirations and decontamination with the use of plants. Green roofs play a significant role in sustainable drainage systems [BARYŁA *et al.* 2018b; BUS *et al.* 2016; PALLA *et al.* 2010; PE CZKOWSKI *et al.* 2018; SOB CZYK, MROWIEC 2016; VILLARREAL, BENG TSSON 2005]. In addition to hydrological abilities, green roofs decrease the effect of urban heat islands [WONG, JIM 2015], decrease energy usage by cooling the roof in the summer period [BANTING *et al.* 2017], create a habitat for plants and animals, thus improving urban biodiversity [CATALANO *et al.* 2018; EMILSSON *et al.* 2007; KÖHLER 2006], improve the aesthetics of cities [BENG TSSON *et al.* 2005; STOVIN *et al.* 2012; SZOTA *et al.* 2017]. The environmental benefits stemming from the construction of green roofs outweigh their limitations, such as the high costs of capital and conservation, supporting the use of these solutions in urbanized areas. Construction-wise, green roofs are multi-layer structures where each of the layers plays an important part

in the structure and contributes to the whole [BUFFAM *et al.* 2016; MORGAN *et al.* 2013; ZHANG, GUO 2013]. Traditionally, a drainage layer, the purpose of which is to retain water for plants and safely drain away its excess to the drainage system, is located above the layer of hydro-insulation and protective layer. The next layer in the system is the filtration layer, protecting the layers beneath against the penetration of small particles of suspensions washed away with rainwater from the roof substrates. The surface part of green roofs comprises the layer of substrate along with the vegetation growing on it. All layers above the hydro-insulation can influence rainwater retention values. In the case of the drainage layer, mineral drainage of aggregates does well to fulfil the role of storing and draining water. Single-fraction mineral aggregates (with the exception of limestones and crushed concrete), as well as light artificial aggregates (e.g. LWA-light weigh aggregate) can be used as drainage. Loose powdery materials containing lime should not be applied due to the negative influence on drainage devices over the course of their use [DAFA 2015]. An advantage of aggregate-based drainage is the possibility of flexibly adjusting the depth of the layer as well as creating counter-slopes in the structure. Due to the better possibilities of condensing and ensuring plant roots an additional supply of water, it is advisable to apply crushed aggregates. The binding guidelines for mineral aggregates for drainage are PN-EN 13242, whereas for light aggregates – PN-EN 13055. In addition to mineral aggregates, the drainage layer can be made of profiled artificial aggregates or geosynthetics [DAFA 2015]. When selecting the drainage layer, materials that are not harmful to the environment and plants, as well as being compatible with other materials and resistant to the effects of atmospheric factors ought to be selected [DAFA 2015]. The drainage selection criteria are very broad. Firstly, the loading possibilities of the structure ought to be assessed, since aggregate-based drainage systems significantly load the structure. The weight of a 5-centimeter layer of drainage made of aggregate saturated with water is anywhere from $30 \text{ kg}\cdot\text{m}^{-2}$ (crushed kermesite) to $90 \text{ kg}\cdot\text{m}^{-2}$ in the case of natural aggregates [Laboratorium Dachów Zielonych undated]. Drainage systems made of synthetics do not weigh much, even together with the stored water, i.e. from 0.3 to

$25 \text{ kg}\cdot\text{m}^{-2}$. Another criterion is the compression strength; aggregate-based drainage always reveals a high or very high value of this parameter. This is not so in the case of synthetic drainages, as their compression strength is strictly connected with their structure. In the case of ensuring high compression strength, drainage systems made of synthetics are filled with aggregate. Another important aspect is the ability to retain water by the drainage layers. Studies carried out by BARYŁA *et al.* [2018a] on the influence of the type of drainage layer (washed gravel, kermesite, drainage mat) on the amount of retention showed, over the three-year course of studies, the highest retention in the model with the drainage mat. HAKIMDAVAR *et al.* [2014] determined the influence of the drainage layer on the reduction of the peak runoff wave and change in the time that the drainage of the rainfall occurs. Studies carried out by KARCZMARCZYK and KOCIK [2017] on the influence of the thickness of the reactive drainage layer (1, 2 and 5 cm thickness) showed that the retention ability resulted mainly from the type of applied substrate, while the presence and thickness of the drainage layer did not have an influence on its changes. The small number of studies regarding the influence of the thickness and type of drainage layer on the retention ability of green roofs prompted the author to carry out studies in this scope. The article undertook the topic of using two mineral aggregates as the drainage layer on green roofs. The aim of the study was to: 1) determine if the drainage layer of a green roof is a significant factor influencing the retention of rainwater; 2) assessing the influence of the thickness of the drainage layer (5, 10 cm) on the amount of retention on green roofs; and 3) revealing the differences in the retention abilities of two widely applied materials (Leca®, quartzite grit) used as the drainage layer on green roofs.

MATERIALS AND METHODS

The influence of the thickness of the drainage layer on the amount of runoff was determined in a field experiment during the period 01.07–30.09.2018 (Fig. 1). Four columns with a diameter of 320 mm were filled with two types of drainage layer – lightweight expanded clay aggregate

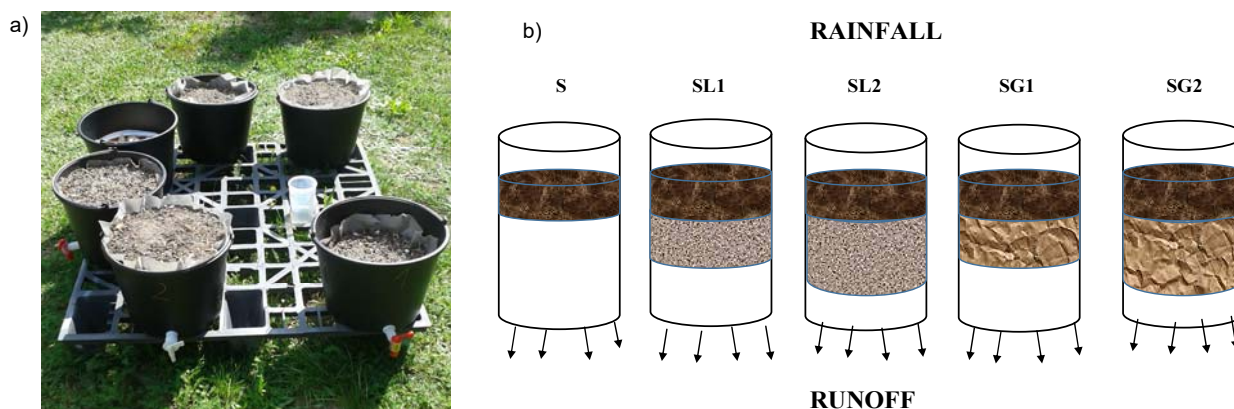


Fig. 1. Diagram of test stands: a) view of test stand in field, b) diagram of test stands; S = intensive substrate, SL1 = Leca® substrate with a thickness of 5 cm, SL2 = Leca® substrate with a thickness of 10 cm, SG1 = substrate and quartzite grit with a thickness 5 cm, SG2 = substrate and quartzite grit with a thickness 10 cm; source: own elaboration

(Leca® Saint-Gobain Construction Products Polska sp. z o.o.) and single-fraction mineral aggregate of quartzite grit. The Leca® is a lightweight construction material used in civil engineering, geoinforming, agriculture, horticulture and environmental protection [Leca undated]. One of the columns was filled with an intensive substrate and marked as S, two columns were filled with substrate as well as Leca® with a thickness of 5 and 10 cm and marked as SL1 and SL2 respectively, and two columns were filled with a substrate and quartzite grit, 5 and 10 cm in thickness, marked as SG1 and SG2 (see Table 1). A filtration layer was placed between the drainage layer and the substrate (polypropylene geotextile Polyfelt TS 20, endurance class GRK 2, weight of 0.125 kg·m⁻²).

The physical properties of aggregates were described in accordance with: particle size distribution PN-ISO 11277:2005, density PN EN 1097-3:2000, porosity PN-EN 1936:2010. The bulk density of the analysed aggregates was 1400 (kg·m⁻³) for the quartzite grit, and 320 (kg·m⁻³) for Leca®. Grain diameters for the quartzite grit ranged from 15 mm to 40 mm, and for the Leca® aggregate from 4 mm to 10 mm respectively (see Table 2). For a drainage layer material the grain size is an important determinant of the water holding capacity [BEATTIE, BERGHAGE 2004]. The ability to permanently absorb water i.e. the absorbability was also analyzed. From the point of view of green roof, the absorbability was more efficient for the Leca® (18%), while the quartzite grit was very low at only 1%.

Table 1. Physical characteristics of substrates used in the study

Parameter	Unit	Value
Content of fractions under 0.063 mm	% mass	5
Content of fractions 0.05–2 mm	% mass	65
Content of fractions 2–20 mm	% mass	30
General porosity	%	≥50
Maximum water holding capacity	%	≥35
Organic matter content	%	9
Water permeability mod. K_{fmod}	mm·min ⁻¹	5
Weight of substrate in moist state (bulk density)	kg·m ⁻³	1 350
Weight of substrate in a state of complete water saturation	kg·m ⁻³	1 700
Foreign matter content	%	<0.1

Source: own study.

Table 2. Basic physical properties of the applied aggregates

Physical properties	Unit	Aggregate	
		quartzite grit	Leca®
Particle size	mm	15–40	4–10
Dry density	kg·m ⁻³	1400±15%	320±15%
Porosity	%	40	48
Absorbability	%	1	18

Source: own study.

The granulometric composition of the substrate was described in accordance with PN-88/04481, water permeability, maximum water holding capacity, weight of the substrate in a state of full saturation with water, organic matter content, and foreign matter content were determined in accordance with DAFA [2015]. A fresh intensive substrate comprised of: compost, perlite, terraton, lava and crushed brick was used in the experiment.

The density of each substrate was 4 cm; applying various thicknesses in individual test trays would have changed the retention abilities, making it more difficult to compare the results of the experiment. The volume of the runoff was measured by hand following each rainfall. The measurement of moisture content and temperature in the layer of the substrate was carried out using a WET-2 probe. The rainfall depth was measured next to the trays using a dish placed at the height of 1 m. Based on the conventional approach involving the determination of atmospheric rainfalls, recommended and assumed in other “green-roof-type” studies, rainfall events divided every six or more hours and were classified as independent events [BERRETTA *et al.* 2014; GETTER *et al.* 2007; PALLA *et al.* 2012; SPEAK *et al.* 2013; STOVIN *et al.* 2012; 2013; VANWOERT *et al.* 2005; VOYDE *et al.* 2010]. Situations occurred, however, where the runoff from the previous event was still occurring when another event took place. In such cases, two adjacent “events” were combined into one. For each of these events, the retention of the green roof ($R\%$) was determined. Runoff retention from the green roof was calculated as [ZHANG *et al.* 2015]:

$$R = \frac{P - H}{P} \cdot 100\% \quad (1)$$

Where: R = retention (%), P = precipitation (mm) and H = runoff (mm).

The antecedent dry weather period (ADWP) or antecedent dry days, which is the duration of dry period prior to a precipitation event [ZHANG, GUO 2013] was calculated in hours. To identify an environmental factors that may have important role in green roof stormwater retention performance, multiple linear regression (MLR) was adopted for the statistical analysis. Three types of parameters were examined as explanatory variables to green-roof stormwater retention: rainfall, ADWP and soil moisture condition. Statistical analyses were carried out in the STATGRAPHICS Centurion XVI program.

RESULTS OF STUDIES

Over the course of 92 days during which the studies were carried out, each of the columns was supplied with 307.80 mm in the form of atmospheric and simulated precipitation (see Table 3). In this period, 21 rainfall events occurred, of which 12 events did not exceed 10 mm, the maximum dose was 53.10 mm, with the minimal being 1.9 mm. Based on the average value of retention of total rainfalls for all simulated rainfall events, the sequence of maintaining rainfalls was similar S (47.6%) SL1 (57.0%) SL2 (61.3%) SG1 (50.1%) SG2 (52.9%). An analysis of the relationships between rainfalls and retention ability showed that the linear model explains from 16 to 30% variance in retention ability in the rainfall function (Fig. 2a). The ANOVA analysis of variance showed that statistically significant differences do not exist between the groups of retention results for the individual columns $F_{(4,100)} = 0.48$; $p > 0.05$. The additionally performed Mood’s median test did not show statistically significant differences between the groups $p > 0.05$ (Fig. 2b).

Table 3. Experimental data of column leaching experiment

Substrate	S	SL1	SL2	SG1	SG2
Volume of leachate Q (mm)	307.82	307.82	307.82	307.82	307.82
Retention R (%): mean (min–max)	47.60 (0.43–100)	57.00 (3.23–100)	61.31 (10.06–100)	50.10 (2.24–100)	52.86 (5.58–100)
Moisture (%): mean (min–max)	14.32 (3.0–27.0)	12.72 (3.0–25.6)	12.44 (2.1–26.6)	12.72 (3.0–25.6)	12.62 (3.0–25.0)
Substrate temperature T (°C): mean (min–max)	25.81 (19.6–32.7)	24.17 (19.6–31.5)	24.74 (19.0–32.5)	24.57 (18.8–33.2)	24.42 (18.7–33.4)

Explanations: S, SL1, SL2, SG1, SG2 as in Fig. 1.
Source: own study.

Similarity to studies regarding the retention ability of green roofs and retention ability of substrates [BARYŁA *et al.* 2018b], decreases along with an increase in the rainfall depth (Fig. 3). The obtained negative values of correlation S (–0.47), SL1 (–0.46), SL2 (–0.54), SG1 (–0.45), SG2 (–0.48) for $p < 0.05$ showed an average relationship between rainfall depth (mm) and the retention ability of the columns. In studies by PALLA *et al.* [2010], during ten months, data containing 30 individual rainfall events were obtained, where the average retention amounted to 51.5%. Eleven events exceeding 40 mm in depth occurred, and the total controlled amount of rainfall was 1165.1 mm. The obtained retention gave the basis for suggesting that this is proof of excellent results of controlling rainwater. However, from the perspective of drainage engineering, the average retention per rainfall event can be of less meaning than understanding the general yearly retention of a system or its reaction to extreme events. The presented data show that in the case of many greater events, retention was in fact lower than 25%. Because these greater events comprise the majority of total rainfalls, the total volume retained was approximately 35%. A yearly retention efficiency of e.g. 60% should not be used to conclude that the roof will be able to retain 60% or even 30% of a significant rainfall. Similarly, there are many different roof configura-

tions (type and thickness of the substrate, slope, size, method of planting), from which we can expect that they will differ, and the same roof configuration will not show the same characteristics of efficiency in two different climatic conditions. Some Authors suggest, that regional climatic conditions are significant factors influencing green roof retention [BERRETTA *et al.* 2014; VOYDE *et al.* 2010]. At the local scale microclimatic conditions may differ between the roofs due to specific site condition

The next factor analysed in the retention of green roofs are the starting conditions prior to the occurrence of a rainfall antecedent dry weather period (ADWP) [ZHANG, GUO 2013]. Studies carried out by BURSZTA-ADAMIAK *et al.* [2014] showed that retention increases along with an increase in the number of rainless days. In the cited work, as little as one rainless day led to improved retention ability of the green roof. In studies carried out by KARCZMAR-CZYK and KOCIK [2017], such relationship was not observed. In the carried out studies it was shown that, along with an increase in the (ADWP), retention ability increases (Fig. 3). The obtained values of correlation SL2 (0.44), SL1 (0.36), SG1 (0.42), SG2 (0.42) for $p < 0.05$ showed an average correlation between ADWP (h) and the retention ability of columns (Fig. 3a).

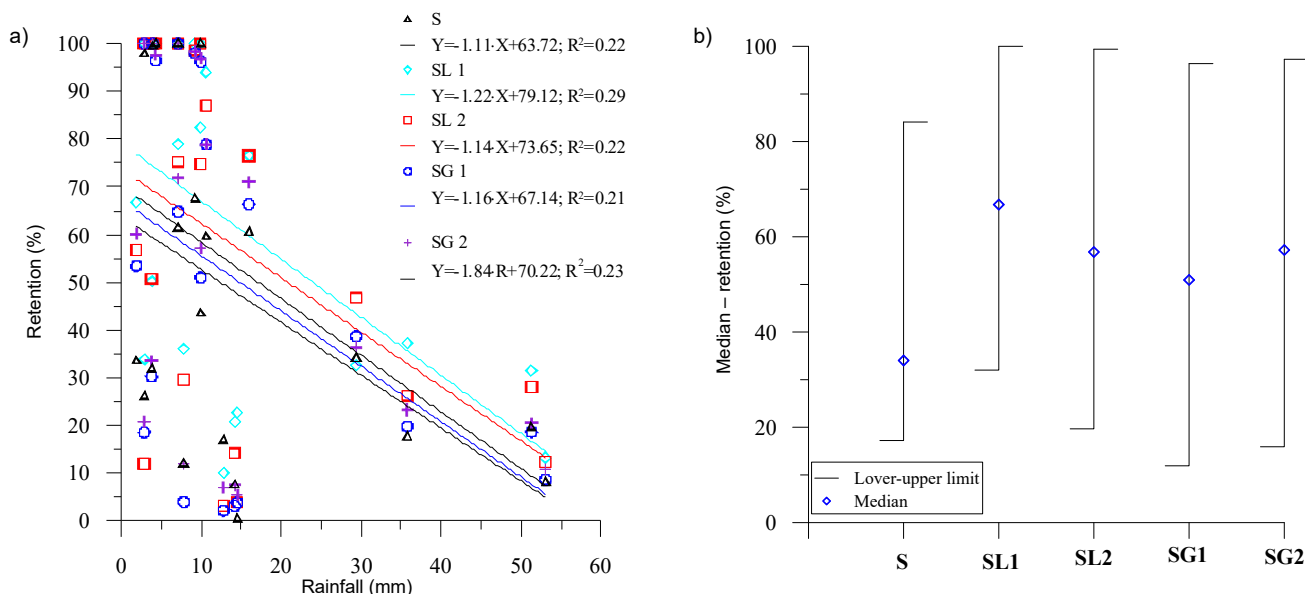


Fig. 2. Relationship between retention R (%) and rainfalls P (mm), as well as in columns with Mood’s interval at 95% level of confidence; S, SL1, SL2, SG1, SG2 as in Fig. 1; source: own study

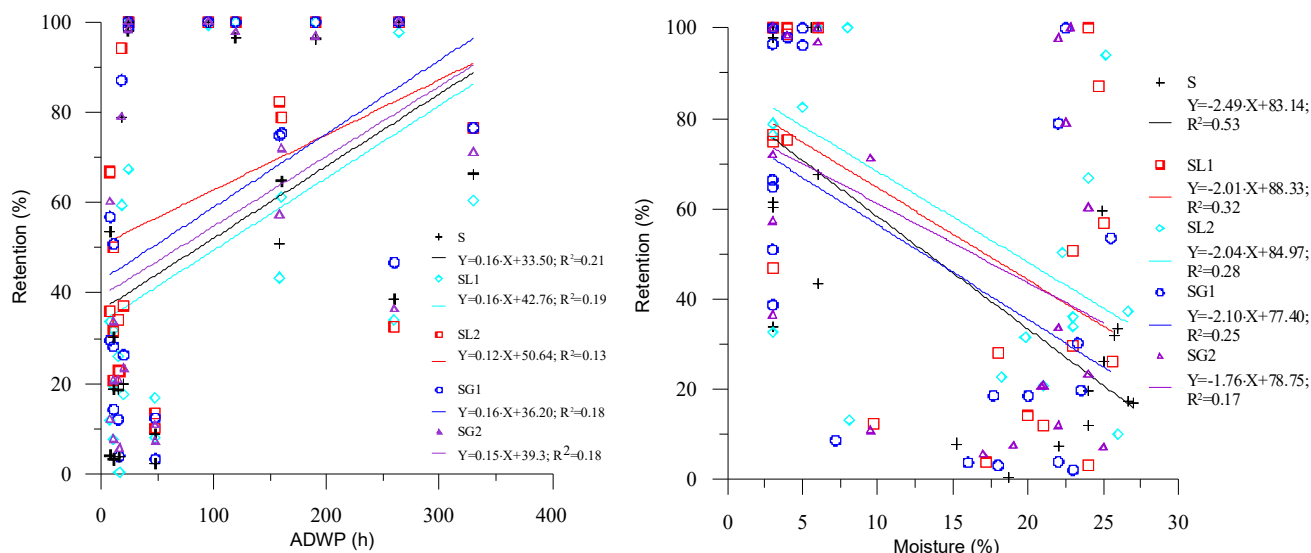


Fig. 3. Relationship between retention (R) and: a) antecedent dry weather period (ADWP), b) moisture content; S, SL1, SL2, SG1, SG2 as in Fig. 1; source: own study

In the case of initial moisture content, the regression coefficients indicate that, along with an increase in initial moisture content, the retention ability of the trays decreases. The obtained negative results of correlation in a linear relationship between retention and moisture content were higher than in the relationship between retention and rainfall depth (Fig 3b). The calculated correlation coefficients in the linear relationship between retention and moisture content were S (-0.73), SL1 (-0.53), SL2 (-0.57), SG1 (-0.50) and SG2 (-0.44), which signifies an average relationship. For each pair of variables, statistically significant linear correlations were shown at a 5% level of significance.

The results showed, that volume of precipitation, moisture substrate, ADWP have a significant effect on green roof retention. The obtained data show that the value of retention decreases with increasing rainfall and substrate moisture, while the ADWP increases the green roofs retention ability. Performed statistical analysis confirmed that rainfall depth and moisture substrate are strongly correlated with retention. Similar results are also reported by UHL and SCHIEDT [2008], STOVIN *et al.* [2015], PALLA *et al.* [2010], SIMS *et al.* [2016], and SOULIS *et al.* [2017].

SUMMARY AND CONCLUSIONS

The drainage layer is one of the factors influencing the hydrological efficiency of green roofs. It is also an important structural element of such roofs due to the effects of inappropriate selection or construction of the layer. One of these are disturbances in the drainage of water infiltrated by the soil substrate or road base. Constantly occurring puddles or soaked soil substrate may indicate improper drainage, as well as plants dying or showing signs of disease. In the event of intense rainfalls, this can even lead to partial inundation or flooding on the green roof. A wet soil substrate is moreover the perfect habitat for mould and fungus. Over the course of carrying out the studies, long-standing water was not observed on the surface, which sig-

nifies good permeability of the substrate as well as the drainage layers. The average ability to retain rainwater in all columns ranged from 50–60%, which is in agreement with the retention ability of green roofs without vegetation cover (60%) given by HARPER *et al.* [2015]. The retention of the substrate was 48%; for a 5 cm drainage layer of Leca®, 10% higher retention was obtained, while a 10 cm layer resulted in 14% higher retention. Smaller differences of the retention value between the substrate and the substrate with drainage layers were noted for quartzite grit. For a 5 cm layer, the difference was 3%, whereas for the 10 centimetre thickness – 5%. The obtained differences between the two aggregates in the retention of rainwater stem from the absorbency of aggregates (Leca® 18%, grit 1%). Faster drying of the substrate with the drainage layer was observed as compare to the tray without the drainage layer. Differences in the individual trays were not significant. It was observed that the amount of rainfall is a factor influencing the amount of water retained on a green roof, which confirms studies carried out by many authors. The initial state of the moisture content of a green roof substrate appears to be a significant factor in reducing the runoff or rainwater from a green roof, as the obtained results pointed to a higher correlation of retention with moisture content than with the ADWP.

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Anna M. BARYŁA

Rola warstwy drenażowej na zielonych dachach w ograniczaniu odpływu wód opadowych z terenów zurbanizowanych

STRESZCZENIE

Istotną rolę w zrównoważonych systemach drenażu odgrywają zielone dachy. Są powierzchniami chłonnymi w odniesieniu do wód opadowych, które retencjonują w profilu i za pomocą roślin. Biorą zatem czynny udział w poprawie warunków klimatycznych miasta, a szerzej bilansu wodnego terenów zurbanizowanych. Jednym z czynników wpływających na wydajność hydrologiczną zielonych dachów jest warstwa drenażowa. W artykule przedstawiono wyniki badań kolumnowych przeprowadzonych w warunkach polowych, w których porównano retencyjność dwóch kruszyw wykorzystywanych jako warstwa drenażowa na zielonych dachach – keramzytu i grys kwarcytowego. Średnia retencja substratu wyniosła 48%, dla 5 cm warstwy drenażowej z Leca® wyniosła 57%, dla warstwy 10 cm średnia retencja wyniosła 61%. Dla grys kwarcytowego średnia retencja wyniosła dla 5 cm warstwy drenażowej 50%, dla 10 cm warstwy drenażowej 53%. Największą retencję uzyskano w kolumnie z substratem i 10-centymetrową warstwą keramzytu. Wykazano, że keramzyt jest lepszym materiałem retencyjnym niż grys kwarcytowy. Początkowy stan wilgotności podłoża z zielonego dachu wydaje się być istotnym czynnikiem w redukcji odpływu wód opadowych z dachu zielonego. Uzyskane wyniki wilgotności początkowej dały silniejszą korelację niż czas pomiędzy opadami

Słowa kluczowe: *odpływ, retencja, warstwa drenażowa, zielony dach*