EVALUATION OF ROOF SUBSTRATE RETENTION PROPERTIES UNDER DIFFERENT MOISTURE CONDITIONS

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Abstract

A laboratory analysis of the retention properties of a roof substrate focused on the initial moisture conditions of Bratislava roof substrate (low and moderate substrate moisture). The water retention capacity of the substrate was investigated by simulating a 15-minute rainfall event with intensities of 1.3 mm/min, 2.7 mm/min, and 3.8 mm/min. The effect of the depth of the substrate (7 and 10 cm) was also analysed. The results showed that a substrate with an initial moisture content of < 5% can retain a larger volume of runoff. It should be noted, however, that this analysis was for only one layer of a vegetated roof. To obtain more comprehensive results, it is necessary to carry out measurements in combination with all the relevant layers of a roof system that contribute significantly to the retention of runoff.

Keywords

Runoff, Moisture conditions, Roof substrate, 15-minute rainfall

1 INTRODUCTION

The gradual change in climatic conditions has encouraged urban areas to incorporate blue-green infrastructures. Frequent droughts, extreme temperatures, and intense, short-term rainfall events are key factors that encourage their introduction. These extreme events lead to significant financial losses, environmental damage, and, last but not least, losses of human life. Although we cannot prevent the climate change, we can mitigate its negative impacts through appropriate measures.

A blue-green infrastructure is a complex network of elements involving water and green systems. Its main objectives are to manage stormwater efficiently, improve the microclimate by greening urban spaces (e.g., mitigating the heat island effect), and provide other environmental and social benefits. This type of infrastructure includes various strategic adaptation measures and plans adapted to the specific needs and objectives of the area.

According to the Catalogue of Selected Adaptation Measures of the Slovak Environmental Agency, there are several types of measures in the rural areas, such as non-forest woody vegetation, windbreaks, grassed seepage strips, infiltration trenches, swales, terraces, and flow profile modifications. In the urban areas, these include rain gardens, residential greenery in street spaces, grassed and permeable areas in parking lots, vegetated walls, and vegetated roofs [1].

Studies have demonstrated increasing urbanisation, with approximately 67% of the population expected to live in cities by 2050 [2]. This growth in population is leading to an increased demand for real property, resulting in a rise in housing construction and the expansion of impermeable surfaces. These areas accumulate pollutants such as oils, heavy metals, pesticides, animal waste, and stormwater that runs off inefficiently. Polluted stormwater can contaminate watercourses, thereby degrading their quality. It is therefore essential to implement appropriate adaptation measures, which are tailored to the specific needs of the site.

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In this paper, we will focus on one type of adaptation measure, namely extensive vegetated roofs. Our experimental measurements will be oriented towards the composition of a vegetated roof with Bratislava's extensive roof substrate, and we will analyse and compare its retention capacity under different moisture conditions.

Hydrological properties

Vegetated roofs can retain a greater volume of rainfall in the substrate, which effectively reduces runoff compared to traditional roofs, where runoff occurs almost immediately (Fig.1). The degree of runoff reduction is influenced by various factors such as the type of vegetation, the composition of the roof substrate, the initial water content, the slope and design of the roof, as well as the current meteorological conditions and the nature of the rainfall. Studies have documented average runoff volume reductions based on individual rainfall events, seasonal data, or annual cumulative rainfall. A comparison of the results from the different studies is limited by differences in climatic conditions, roof characteristics, the duration of measurements, and methods used. Accounting for runoff in winter, when snow accumulates and subsequently melts, is also essential.

Peak runoff, which is defined as the maximum volume of runoff from precipitation, is a key hydrological parameter. In a 2.5-year study of an experimental green roof with 22 rainfall events, hydrological research in the UK demonstrated a 60% reduction in peak flow compared to a control roof [3].

Vegetated roofs not only reduce the volume of peak runoff but also delay it, thereby mitigating stormwater's negative impacts. They act as catch basins that slow down the peak and onset of runoff. The roof's initial moisture content and composition affect this process.

A review of the literature suggests that vegetated roofs can reduce total runoff volume by between 30% and 90%, peak runoff by 20% to 90%, and delay its onset by up to 30 minutes [4], [5], [6], [7]. These studies do not focus on the design aspect of vegetated roofs, but highlight their importance and expected benefits for water management in urban environments.

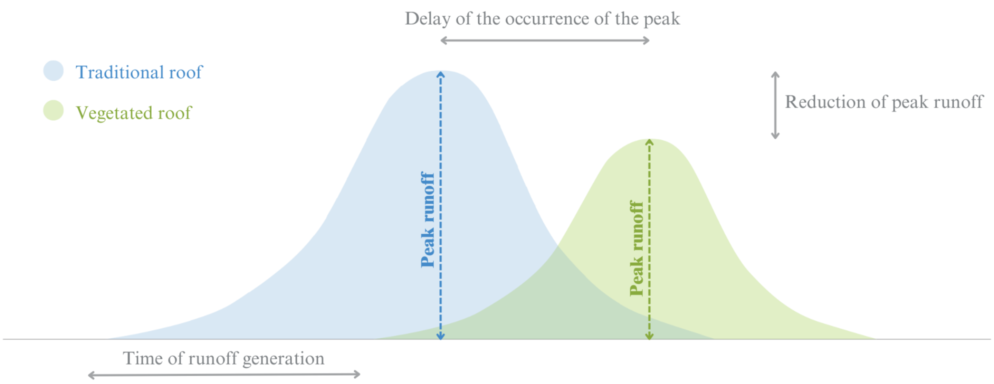

Fig. 1 Precipitation runoff discharge: traditional and vegetated roof.

Roof substrate

A roof substrate (the growing medium) plays a key role in promoting plant growth and also contributes to slowing down and retaining stormwater runoff. The roof substrate is an essential component of vegetated roofs. When properly formulated, including the use of lightweight admixtures, a high load on the building structure can be avoided.

There is a wide range of substrates on the market, which are adapted to the specifics of regions and climatic conditions, and the choice of which depends on the roof load and the type of vegetation. The ideal substrate should provide adequate nutrition for plants and contain a mixture of organic matter, lightweight mineral aggregates, natural and artificial minerals, and recycled materials. The physical properties of the substrate, such as its low bulk density, high water-holding capacity, optimum organic content for vegetation growth and sorption capacity, which minimise the risk of water contamination, are also important.

A roof substrate significantly affects the retention of stormwater runoff, which contributes to the reduction and delay of peak flow in a drainage system. In addition, vegetated roofs benefit from evapotranspiration processes

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that reduce runoff volume due to the vegetation planted. When implementing vegetated roofs, it is important to pay attention to stormwater management, specifically the reduction of the total runoff volume, the reduction of peak flow, and the time delay of any runoff.

Many studies on roof substrates also discuss the effect of substrate height; by increasing the substrate height, the retention capacity of the substrate is expected to increase [8], [9].

In this research, we tested commercially available Bratislava roof substrate, composed of brick rubble, lava and compost. It is used in the construction of extensive vegetated roofs with a minimum layer depth of 6 cm and is suitable for both flat and pitched roofs. According to the producer's data, the dry weight of the substrate is 0.85–1.0 t/m³, while in the wet state it can reach up to 1.39 t/m³ [10]. The package leaflet gives details of its chemical and physical properties (Tab. 1).

Tab. 1 Chemical and physical properties by supplier.

Properties	**Value**
Moisture content in % by weight	max. 10
Content of combustible substances in dry matter % by weight	min. 3
Nitrogen content as N in % of dry substances	min. 0.07
Phosphorus content as P_2O_5 in % of dry substances	min. 0.1
Potassium content as K_2O in % of dry substances	min. 0.3
El. conductivity s/cm	max 1.2
pH value	6.5 - 8.5
Grain size above 20 mm	0

These components differentiate the tested substrate from standard substrates used on vegetated roofs, which typically use lightweight expanded clay aggregate, perlite or mineral wool. The brick rubble and volcanic lava provide structural stability and sufficient aeration of the substrate while maintaining a low bulk density. The compost serves as a source of essential nutrients while supporting microbial activity, which is crucial for healthy vegetation growth. In addition, the use of locally available materials, such as brick rubble and lava, contributes to reducing the environmental burden associated with the transport and logistics of feedstock [11].

2 METHODOLOGY

Laboratory analysis

The laboratory measurements we undertook will be analysed based on the differing initial moisture conditions of the Bratislava roof substrate. The laboratory measurements were divided into two phases, which are shown in Fig. 2.

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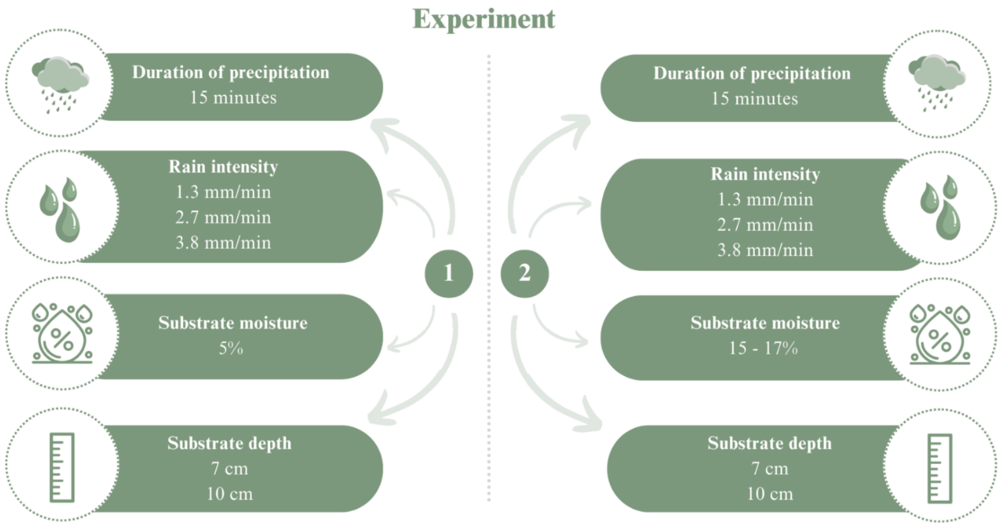

Fig. 2 Schematic diagram of the experiment.

The first phase included a substrate with a moisture content of up to 5% (a dry substrate), while the second phase had a substrate with a moisture content of approximately 15% (a wet substrate with a measured initial moisture content range of 15–17%) (Fig. 3). The rainfall simulation lasted 15 minutes, and the intensities were set at 1.3 mm/min (= 19.5 mm/15 min), 2.7 mm/min (= 40.5 mm/15 min) and 3.8 mm/min (= 57 mm/15 min). The rainfall had to be divided into several periods (3, 6, 9, 12, 15 minutes) to accommodate moisture measurements.

The moisture parameters were monitored using a Delta-T Devices HH2 moisture meter at the beginning, during and at the end of the measurements (Fig. 4). At the end of the measurements, the maximum moisture content of the substrate should have been reached (about 30%). The substrate retention capacity at 15% moisture was expected to be lower than at 5%. The study aimed to analyse the behaviour of the substrate at different initial moisture levels, particularly by the amount of precipitation retained and the time required for its absorption. The rainfall simulation was provided by an Eijkelkamp portable rainfall simulator with a capacity of 2.3 litres and a surface area of 0.0625 m², which allows for the intensity and duration of the rainfall to be adjusted. The accuracy of the commercial Eijkelkamp rainfall simulator (with certificate) was verified directly based on the actual simulated rainfall volume over time. The reliability of the results was confirmed by repeated measurements and rainfall intensity evaluation.

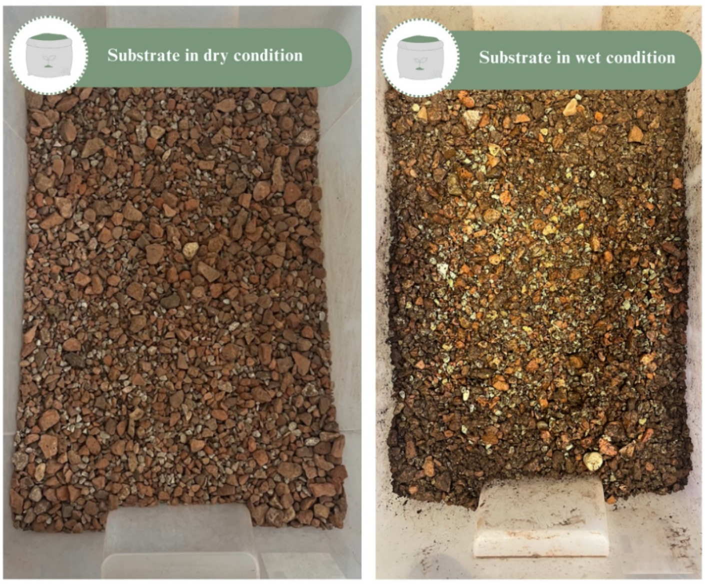

Fig. 3 Roof substrate in dry and wet conditions.

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Fig. 4 Moisture measurement of the roof substrate sample.

3 RESULTS

The laboratory analysis was focused on comparing the retention capacity of the Bratislava roof substrate samples at different initial moisture levels, namely at values below 5% and around 15%. The experiment was aimed at evaluating the effect of different initial moisture conditions on the retention capacity of the substrate during short-term rainfall events with different intensities. The results of the measurements are recorded in Tab. 2 and Tab. 3. A graphic representation of the results is given in Fig. 5.

Tab. 2 Measurement results - depth of roof substrate: 7 cm.

Tested substrate depth (cm)	Initial moisture (%)	Rain intensity	Total precipitation (mm)	Time of runoff formation (min)	Runoff from rain (ml)	Sediment (g)	Substrate retention rate (%)	Difference (%)
7 cm	< 5% < 15%	1.3 mm/min	19.5 19.5	5 2.15	47 720	0.23 2.29	96.5 42.9	53.6
7 cm	< 5% < 15%	2.7 mm/min	40.5 40.5	2.6 0.44	849 1968	3.07 5.51	66.3 24	42.3
7 cm	< 5% < 15%	3.8 mm/min	57 57	0.55 1.36	1647 2282	3.25 3.42	53.3 28	25.3

Tab. 3 Measurement results - depth of roof substrate: 10 cm.

Tested substrate depth (cm)	Initial moisture (%)	Rain intensity	Total precipitation (mm)	Time of runoff formation (min)	Runoff from rain (ml)	Sediment (g)	Substrate retention rate (%)	Difference (%)
10 cm	< 5%	1.3 mm/min	[illegible]	5.8	45	[illegible]	96.4	25.3
	< 15%		19.5	5.59	382	1.46	71.1	
10 cm	< 5%	2.7 mm/min	40.5	3.2	394	1.19	84.5	20.5
	< 15%		40.5	4.31	870	3.58	64	
10 cm	< 5%	3.8 mm/min	57	1.26	1509	2.1	56.9	12.7
	< 15%		57	2.42	1885	7.01	44.2	

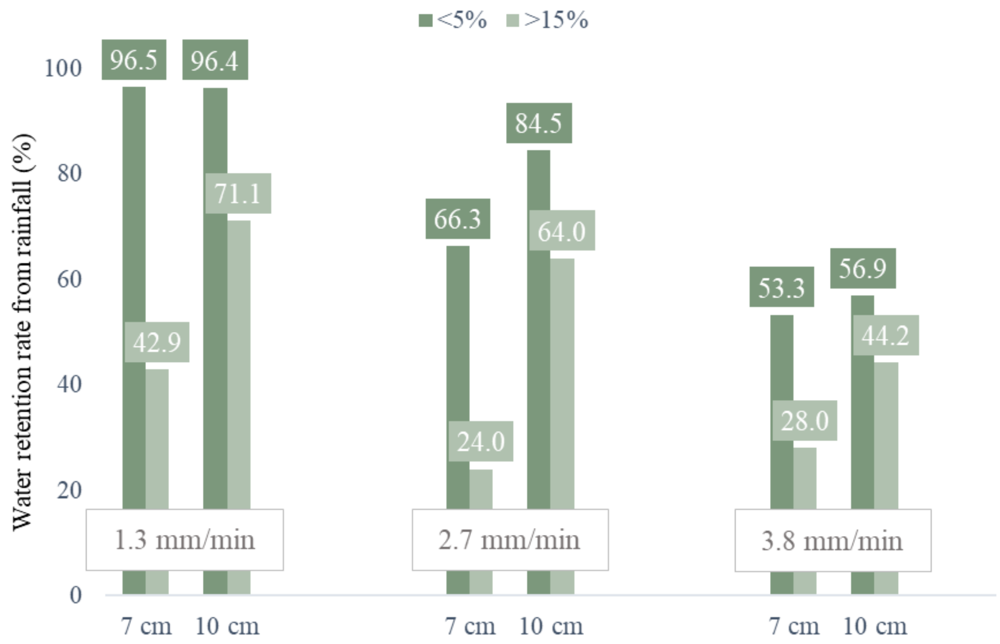

Fig. 5 Comparison of the substrate retention under different initial conditions (<5% and approximately 15%) of 15 min rainfall.

<u>7 cm layer of roof substrate</u>

At a rainfall intensity of 1.3 mm/min (total rainfall of 19.5 mm), the retention at an initial substrate moisture content below 5% was 96.5%. At higher initial moisture content (above 15%) the retention dropped to 42.9%. There was a difference of 53.6%. At a rainfall intensity of 2.7 mm/min (total rainfall of 40.5 mm), the retention at the initial moisture content below 5% was 66.3%, while at the initial moisture content above 15%, the retention was 24%. This was a decrease of 42.3%. At a rainfall intensity of 3.8 mm/min (total rainfall of 57 mm), the retention at the initial moisture content below 5% was 53.3%, while at the initial moisture content above 15%, it was 28.0% This was a decrease of 25.3%.

<u>10 cm layer of roof substrate</u>

At a rainfall intensity of 1.3 mm/min (total rainfall of 19.5 mm), the retention at the initial moisture content below 5% was 96.4%, while it dropped to 71.1% at the initial moisture content above 15%. It was a difference of 25.3%. At a rainfall intensity of 2.7 mm/min (total rainfall of 40.5 mm), the retention at the initial moisture content below 5% was 84.5%, while it was lower at 64.0% at the initial moisture content above 15%. This was a difference of

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20.5%. At a rainfall intensity of 3.8 mm/min (total rainfall of 57 mm), the retention at the initial moisture content below 5% was 56.9%, while at the initial moisture content above 15%, it was 44.2%. There was a decrease of 12.7%.

It is essential to understand how the substrate responds during prolonged rainfall events, especially considering the changing seasons, which influence the moisture conditions of the substrate. Under ideal conditions, a dry substrate has a higher retention capacity, reducing runoff. However, the purpose of comparing different moisture levels is to evaluate how a substrate with elevated initial moisture content (such as 15%, as compared to the initial 5%) retains water relative to a dry substrate. It is important to note that the initial moisture content of the vegetated roof can influence the water transport through the substrate and vegetation during the dry seasons.

4 DISCUSSION

The results confirmed that the retention capacity of the roof substrate decreases at higher initial moisture content. At moisture content above 15%, the water absorption capacity was significantly lower compared to the dry substrate (below 5%). The thicker layer of substrate (10 cm) had a higher retention capacity than the thinner layer (7 cm), but its capacity also decreased at higher moisture content. Under extreme rainfall, the retention capacity of the 7 cm substrate was reduced by 25–54%, while for the 10 cm layer the reduction was 12–25%. Higher rainfall intensity led to more runoff, especially with wetter substrate, indicating the risk of increased runoff with frequent rainfall without sufficient drying of the substrate. The extent of reduced runoff is greater with a layer thickness of 7 cm than with a substrate thickness of 10 cm. This was not expected. It should be noted that the extent of runoff volume is greatly influenced by the intensity of the rainfall. These findings are in accordance with previous studies on vegetated roof substrates. For example, research has shown that the composition of the substrate can significantly influence its retention performance. Specific inorganic materials such as exfoliated vermiculite and expanded perlite can improve water retention capacity, resulting in a water retention capacity of approximately 39.4%. This highlights the importance of selecting appropriate substrate materials to optimise stormwater retention efficiency. In addition, a clear correlation between initial substrate moisture content and runoff coefficients was found in research on runoff retention efficiency on extensive vegetated roofs. The results suggest that substrates with higher initial moisture content show reduced water storage potential, leading to increased runoff volume, which is consistent with the trends observed in this study [12]. Berretta et al. found that moisture loss in extensive vegetated roofs during dry periods was influenced by temperature, substrate moisture, and vegetation. They observed reduced evapotranspiration when moisture availability was limited and higher moisture loss with vegetation. This supports our findings, highlighting the significant role of initial substrate moisture in retention capacity [13].

In summary, my research findings are in accordance with existing literature, which highlights that both initial moisture content and substrate composition significantly impact the water retention capacity of vegetated roofs. These findings are important in the design of vegetated roofs, where the use of retention tanks to capture excess water may be an appropriate solution. The study focused on only one layer of the vegetated roof (Bratislava roof substrate), whereas in real conditions, additional layers, such as vegetation, can improve the overall absorption capacity of the system. Future research should focus on more complex vegetated roof models and their effectiveness under different conditions.

5 CONCLUSION

The laboratory analysis confirmed the hypothesis of a reduced retention capacity of the roof substrate at an elevated initial moisture content. This is due to the fact that the substrate particles are fully saturated at high humidity levels, which increases runoff, as the substrate is no longer able to absorb a larger volume of water. The substrate at an initial moisture content higher than 15% reached a maximum moisture capacity of 32.6% when measured.

Two heights of roof substrate were tested. The substrate samples were in a dry (up to 5% moisture content of the medium) and a wet condition (approximately 15%) at the beginning of the extreme rainfall simulation. It was confirmed that the higher substrate depth had a higher retention capacity for both initial moisture contents. The reduction in retention capacity of the 7 cm wet substrate was up to 25–54% for the simulations of three extreme rainfall events (1.3 mm/min, 2.7 mm/min, 3.8 mm/min). In the case of moist substrate with a height of 10 cm, the retention capacity was reduced up to 12–25%. If the initial substrate moisture content at the start of the extreme

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rainfall was approximately 15%, the reduction in runoff from the vegetated roof would have been substantially less.

Such experiments have a significant impact on the design of vegetated roofs. In the case of frequent rainfall, the substrate can reach high moisture levels, which, if not sufficiently dried out between rainfall events, could lead to an increase in the volume of runoff. In this context, consideration should be given to the inclusion of storage tanks to provide for the retention of excess water, which could then be utilised in drier periods.

It should be emphasised that this laboratory analysis has only focused on one layer of vegetated roofs, namely the Bratislava roof substrate. However, in an actual vegetated roof design, other layers, such as the vegetation layer, will also be present, which may contribute to higher moisture absorption.

Laboratory measurements also demonstrated the influence of rainfall intensity. Runoff generation is higher at higher rainfall intensities, and in addition, the energy of the rain was also reflected in the sediment weight. Increased initial moisture had a significant effect on sediment weight.

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