The Effects of Substrate Types on Rainwater Control on a Container Green Roof

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Abstract: Green roofs have been recognized as a valuable approach to adjust for urban microclimate, purifying rainwater and increasing biodiversity in urban spaces. Besides, it can be used to control rainwater runoff effectively. The adsorption function of green roofs on rainwater runoff mainly depends on the interception effect of the vegetation layer and the absorption and storage effect of the substrate layer. The effects of rainwater runoff are impacted by varying substrate types. In this study, the formation time of runoff for silicate mixed matrix (grass soil: pumice = 3:1) and high-temperature combustion oxide mixed matrix (grass soil: slag = 3:1) were measured and compared in a rainfall simulation experiment. The different responses between their runoff intensity and time were analyzed. The results showed that the runoff formation time was 255 min for the silicate mixed matrix and the runoff peak time was 310 min when the rainfall intensity was 0.3 mm/min and the substrate thickness was 300 mm. The runoff formation time was 230 min for the high temperature combustion oxide mixed matrix and the runoff peak time was 290 min in the same conditions. Both the runoff formation time (over 9.8%) and the peak runoff time (over 6.5%) for the silicate mixed matrix were longer than the time for the high temperature combustion oxide mixed matrix. Based on the results from this study, the silicate mixed matrix is more effective than the high temperature combustion oxide mixed matrix in control rainwater runoff on green roofs.

1. Introduction

More and more green spaces have been replaced by impervious surfaces with the continuous advancement of country's urbanization. In recent years, urban waterlogging disasters caused by local climate change and the imperfect urban drainage systems have occurred frequently in Beijing, Nanjing, Wuhan, Changsha and other places. Therefore, exploring effective measures to alleviate urban waterlogging and solving the problem of rainwater storage is becoming a research hotspot of scholars at home and abroad.

Roof greening can be used to intercept and store rainwater effectively, reduce the total runoff of rainfall, and delay the time of runoff as the “fifth facade” of the city, which is beneficial to reduce urban waterlogging and improve urban water environment. Therefore, it has become an effective way to alleviate urban rainwater at present. The effect of roof greening on reducing rainfall and runoff depends on many factors, and domestic and foreign scholars are enthusiastic about it. The interception capacity of the roof matrix varies differently under different regions and different environmental conditions. Stovin et al. used 29 months rainfall data in Sheffield England to analyze the rainwater regulation capability of experimental green roofs, and its average interception rate was 50.2%; Razzaghmanesh et al. found that the average interception rate of extensive green roofs is...
74.02% in arid climate conditions; Nawaz et al. analyzed 30 rainfall events in temperate climates and found that the interception rate of green roofs ranges from 3.6% to 100%, and the average interception rate is 66%. In addition, some scholars believe that the interception rate of green roofs is related to factors such as rainfall characteristics and dry time before rain. Stovin found that the increase in the dry time before rain can improve the rainwater retention capacity of the green roof. At the same time, studies have shown that the thickness, type and slope of the roof matrix itself also affect the effect of rainwater interception. Lee et al. found that the green roof interception rate varies by 42.8%~60.8% when the growth matrix is 200mm deep, the interception rate is 13.8%~34.4% when the growth substrate is 150mm deep. Teemusk studied the rainwater interception potential and runoff water quality of a green roof based on light aggregates of rock wool, lightweight soil, humus and clay. Villarreal et al. studied the water storage capacity of the green roof matrix with the main components of broken bricks and sand. Zhang et al. simulated the rainfall intensity of 50-80mm and found that the retention rate of commercial substrates can reach 51.1%, while the retention rates of volcanic rock bedrock and pastoral soil are 33.6% and 30.4% respectively. If the organic matter mixed with coconut bark and compost bark is added to the matrix, the storage performance of the green roof will be enhanced with the increase of the organic matter content in the matrix. Getter studied the influence of roof greening substrate gradient (2%, 7%, 15%, 25%) on rainfall retention effect, and the results showed that the greater the slope, the smaller the roof greening effect on rainfall retention.

In recent years, there are many types of commonly used roof greening substrates (Table 1). The artificially proportioned lightweight substrates are light in weight and strong in water retention, which can well meet the design load of roof greening. However, there is currently a lack of quantitative research on light-weight substrates in terms of substrate ratio and water retention capacity. Therefore, we selected two different substrate types for rainfall simulation test determination aiming to study the influence of substrate types in lightweight green roofs on rainwater retention, to explore the best substrate formula suitable for lightweight container roof greening and to provide scientific basis for roof greening and rainwater management.

| The type of substrate | Ratio  |
|----------------------|--------|
| Grass and charcoal: Zircon: Sand | 7:2:1 |
| Yellow mud: Organic fertilizer: synthetic soil | 6:2:2 |
| Roof greening dedicated nutrient soil | — |
| Grass and charcoal: wood chips: organic fertilizer: pearl rock | 5:3:1:1 |
| Soil: Artificial light bone | 3:1 |
| Soil: Artificial light bone | 5:3 |
| American foam-like culture | — |

2. Materials and Methods

2.1. Study Site

The study site was established in the greenhouse of the Shanghai Institute of Technology with an ambient temperature of 18-25°C. The Shanghai area is a subtropical monsoon climate with a mild climate and abundant rain. There are about 230 frost-free periods throughout the year, and the annual average rainfall is about 1200 mm. The annual rainfall in Shanghai is concentrated from June to September and the total number of rainy days is about 130 days, of which about 90 days are medium and light rain. In terms of extreme rainfall, Shanghai area is affected by the combination of typhoon trough and hot and cold air. The rain intensity is 27~36 mm/h in 1a and 57~81 mm/h in 5a. The rain intensity is 81~100 mm/h in the case of heavy rainfall in 30a, and the rain intensity is ≥101 mm/h in
the case of rain in 100 a. Huge drainage pressure on the Shanghai area is caused by the heavy rainfall weather, especially the central urban area.

Table 2. Criteria for the classification of rainfall intensity.

| Rainfall level | Total rainfall in 12 hours (mm) | Total rainfall in 24 hours (mm) |
|----------------|---------------------------------|---------------------------------|
| Light rain     | ≤4.9                            | 0.1-9.9                         |
| Moderate rain  | 5.0-14.9                        | 10.0-24.9                       |
| Downpour       | 15.0-29.9                       | 25.0-49.9                       |
| Torrential rain| 30.0-69.9                       | 50.0-99.9                       |
| Heavy rain     | 70.0-139.9                      | 100.0-249.9                     |
| Heavy downpour | ≥140.0                          | ≥250.0                          |

2.2. Methodology

2.2.1. Materials

The green roof runoff is influenced by many factors especially by substrate types. Therefore, exploring the impact of substrate types on runoff is of great significance. Seven kinds of materials such as turf soil, perlite, pumice, vermiculite, zeolite, fly ash, and slag are always regarded to be common roof greening substrates. In terms of composition, the above seven materials can be divided into organic decay (grass soil), silicate materials (perlite, pumice, vermiculite, zeolite) and high-temperature combustion oxide materials (fly ash, slag) (Table 3).

Table 3. Common categories and basic characteristics of substrate.

| The category                  | The material          | Basic characteristics                          |
|-------------------------------|-----------------------|-----------------------------------------------|
| Organic decay                 | Grass and charcoal    | Loose breathability, high organic matter content, strong permeability |
|                               | perlite               | Loose breathability, anti-plate knot           |
|                               | pumice                | Drains are breathable and have many pores     |
| Silicate material             | vermiculite           | Breathable water                              |
|                               | zeolite               | Strong adsorption capacity, fertilizer and water preservation, improve the soil |
| Burning oxides at high        | Fly ash               | Breathable and porous                         |
| temperatures                  | slag                  | Breathable and porous                         |

Grass charcoal soil was used as an essential substrate for green roofs in order to solidify roots. Pumice, zeolite, perlite, and vermiculite showed the similar permeability coefficients \((K=0.000108401)\) and saturated water content \((≈55\%)\) measuring by constant head method and ring knife method respectively. The density of pumice is 0.35 g/cm\(^3\), the density of zeolite is 2.12 g/cm\(^3\), the density of perlite is 2.34 g/cm\(^3\), and the density of vermiculite is 2.57 g/cm\(^3\) measured by the ring knife method again. It can be seen that he pumice stone is lighter under the same conditions, which is more conducive to reducing the load on the green roof. Since there are many types of fly ash and slag cannot be optimized through horizontal comparison, the more easily available slag was selected as the test material. The composition and physical and chemical properties of the slag are shown in Table 4.

Table 4. The composition, physical and chemical properties of selected slag.

| Ingredients                        | Particles \((\mu m)\) | pH         |
|------------------------------------|----------------------|------------|
| 33%SiO\(_2\) + 26%Al\(_2\)O\(_3\) + 2%Fe\(_2\)O\(_3\) + 1%CaO + 38%other ingredient | 10-20                | Weak alkaline |

Only two mixed materials were used as the green roof substrates in order to avoid too many types of substrates and too complicated preparation. The selected types were: turf soil: pumice = 3:1 and turf soil: slag = 3:1 through the analysis of the above seven materials, which were used as representatives
of the selection of green roof silicate substrates and high-temperature combustion oxide substrates (Table 5).

Table 5. The type and ratio of selected substrate.

| Type                                 | Ratio                        |
|--------------------------------------|------------------------------|
| Silicate substrates                  | Grass and charcoal: Flotsie 3:1 |
| High temperature combustion oxide    | Grass and charcoal: Slag: 3:1  |
| substation                           |                              |

2.2.2. Methods
At first, some preparations need to do. Eight 600*600*600 mm containers were selected and divided into two groups for testing, and ceramsite was filled inside the containers with a thickness of 100 mm above the ground. A hole(with a diameter of 10 mm)was drilled at a height of 100 mm from the ground on the outer wall of the container. Next, non-woven fabric was laid on top of ceramsite. At last, the substrate was taken from two pre-prepared substrates with a thickness of 300mm, and ryegrass was planted on the two substrates respectively.

Rainfall simulation: The nozzle-type rainfall device was selected. During the measuring period, the nozzle diameter was selected, and the test device was placed directly under the nozzle, and the rain intensity was changed by adjusting the power of the water pump. The water pump in the rainfall device adopted SZ037-B model Yuehua brand stainless steel centrifugal pump (flow rate 0-30L/h), 0-50hz adjustable frequency motor, and the rain intensity range was controlled between 0-1.35mm/min. (The test used instantaneous rain intensity instead of natural rain intensity, instantaneous rain intensity 0-0.3mm/min instead of light rain, 0.3-0.6mm/min instead of light rain-moderate rain, 0.6-0.9mm/min heavy and medium rain-heavy rain, above 0.9mm/min was extreme rainfall, and the instantaneous rain intensity in the test was referred to as rain intensity in the text). The test used a single nozzle with a diameter of 4 mm, and the nozzle was supported 2m above the container. The effective coverage radius of the test rainfall was $\geq$3m, and the rain intensity was controlled to be about 0.3mm/min.

2.2.3. Statistical analysis
The data records are divided into the following steps. At first, Water outlet was received with a receiving vessel, and the discharge time of the water flowed from the drain hole of each container (Figure 1) was recorded during the measuring period. Next, the total amount of water in the receiving vessel of each vessel every 10 minutes was measured after the runoff was formed. 1/4 of the total water volume was took for each group, which was converted to the rainfall of a single receiving vessel, the runoff intensity Q of the monomer container during this period was calculated, and the relationship of Q-T diagram was showed as Figure 2.

![Figure 1. Runoff formation time of different matrix types.](image-url)
It can be seen from Figure 1 that the flow generation time of silicate substrate with peat soil: pumice = 3:1 was generally longer than that of high temperature combustion oxide substrate with peat soil: slag = 3:1, which indicating that adding a certain proportion of silicate matrix showed better water retention capacity than the high-temperature combustion oxide matrix to a certain extent. The Q-T diagram in Figure 2 showed that the runoff peak of the silicate substrate with peat soil: pumice = 3:1 appeared later than that of the high temperature combustion oxide substrate with peat soil: slag = 3:1, delaying about 20 minutes. The two different types of substrates both adsorbed rainwater in the initial stage, and there was no runoff in this period. As time goes by, the speed of rainfall runoff was faster than the speed of substrate adsorption, in which time the substrate reached the saturation state slowly. The matrix was overloaded and adsorbed at the critical point of saturation. At the same time, the flow of rainwater was greater than the rainfall because of the gravity effect. The matrix water storage capacity reached saturation at last, and the seepage flow was equal to the precipitation, which reaching a steady state.

### 3. Discussion & Conclusions

Based on the social background of urban rain and flood disasters, we aimed to study the influence of substrate types in lightweight green roofs on rainwater retention and explore the optimal substrate types suitable for lightweight container roof greening. We analyzed the runoff formation time of different substrate types through rainfall simulation experiments and studied the relationship of runoff intensity and time of silicate substrates and high-temperature combustion oxide substrates in order to screen the substrate types suitable for container-type green roofs (silicon Mixed matrix of acid salt and humus soil).

Different substrate types showed different processing capabilities for runoff. In the study of Schultz[15], the runoff intensity of different substrates in different periods was compared and analyzed. Teemusk[9] et al. conducted a statistical analysis on the roof matrix runoff and runoff water quality under rainfall and snow cover environments, which did not comprehensively consider the runoff generation time. The rainfall simulation test of silicate mixed matrix (pyrophyte: pumice = 3:1) and high-temperature combustion oxide mixed matrix (pyrophyte: slag = 3:1) were compared by the study, taking into account the time of runoff generation and the occurrence of flood peaks. Successively, it was showed that the silicate mixed substrate runoff formation time is 255 min, and the runoff peak time is 310 min when the rainfall intensity is 0.3 mm/min and the substrate thickness is 300 mm. The high temperature combustion oxide mixed matrix is delayed by about 9.8% on the basis of the runoff formation time (230 min), and the peak runoff time (290 min) lags by 6.5%. It can be seen that the silicate mixed matrix is more suitable than the high temperature combustion oxide mixed matrix to be used by green roof runoff treatment.

![Figure 2. The influence of different matrix types on runoff intensity.](image-url)
Acknowledgement
This research was funded by the Project of the Shanghai Scientific & Technological Committee (19DZ1204006) and the Project of the Special Development Fund for Zhangjiang National Independent Innovation Demonstration Zone, Shanghai (201701-PD-JQ-A5055-007).

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