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The hydrological performance investigation of light weight green roofs made from natural fibres and recycle waste materials for storm water runoff mitigation: A review

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Abstract: Hydrological performance investigation is often required in urban storm water structural design. Green roofs are normally used to provide temporary storage spaces and promoting infiltration, thus mimic pre-development natural hydrologic functions. Therefore, green roofs parameters such as the layers, materials and the depth for each layer must be considered to improve the performance of water retention. At the same time, slope of green roofs also can be factors affecting the green roof runoff retention. Providing a sustainable environment and lightweight green roof are important. Due to the need of sustainable practices to be implemented in construction, there are several research done on using cheap and recyclable materials for green roof building. In striving to find the optimum and sustainable extensive green roof design, the issue of live load in wet conditions is hence, very important. This paper reviews the possible use of recycle materials and natural fibres as a replacement of non-renewable sources for storm water runoff mitigation. It aim to promote the idea of using these waste by combining their usage in both drainage and filter layers. This provides a summary of existing knowledge about the successful use of waste and natural fibres such as rubber crumbs, bio char and palm oil clinker in a green roofs layer. Also help in finding the hydrological performances in green roof to mitigate storm water runoff and the weights (dry and live) as live loads on supporting beams.

Key words: Green roofs; Water retention; Sustainable; Runoff mitigation

1. Introduction

The United Nations [26] predicted that the developing countries population will rise from 5.9 billion in 2013 to 8.2 billion in 2050. Hence, to cater for space expansion due to population rise, urbanization such land clearing and deforestation increases the impervious surface on urban catchments. Additionally, studies indicate global warming may cause increased frequency of rainfall events, leading to increased localized and flash floods [2]. Sustainable Urban Design System (SUDS), Best Management Practices (BMPs), Low impact Development (LID) and Water Sensitive Urban Design (WSUD) offers new insight to reduction controls, such as green roofs, can provide temporary storage spaces and promoting infiltration, thus mimic pre-development natural hydrologic functions. The SuDS approach goes beyond the need to control the quantity of runoff, aiming also to improve urban water quality and provide amenity [24]. Green roof can retain storm water [27], delay peak discharge time [7] and attenuate a peak discharge volume [12][25].

2. Green roofs

As stated by Berndtsson et al. [4], vegetated roofs can play an important role in modern urban drainage because of their ability to slow down and reduce runoff response. on one hand, research shows that green roofs have numerous environmental benefits such as reduce flood risk, improve rainwater runoff quality, mitigate urban heat island, building energy saving and provide urban wildlife habitat. In general, green roof are usually formed by vegetation layer, substrate layer, filter layer, drainage layer and waterproofing layer. Green roofs layer, type, lightweight green roofs, effect of slope in green roofs and also the benefit are discussed to improve the hydrological performances for storm water runoff mitigation.

2.1. Green roofs layers

The layers of green roof material generally remain the same for both extensive and intensive roofs. The upper layer of green roof is vegetation layer comprising of a thick growing substrate (15 cm) and plants [18] [28]. Substrate layer are usually top soil or garden soil. It is the physical support for the plants, where it provides nutrients and should have the capacity to retain water. Following by the filter layer which usually geotextiles membranes. It allows water to cross but not of the substrate small particulates that could clog the cavities in the drainage layer. Next, drainage layer must be able to retain water when it rains, while ensuring good

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drainage & aeration of the substrate and roots. The waterproofing layer protects the building from the roots and water [15].

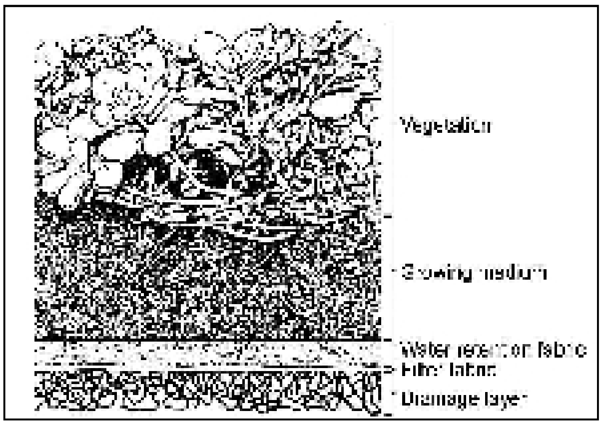

Fig. 1: Cross-section of a representative extensive green roof system including typically used layers [8].

The cross-section of a representative extensive green roof system including typically used layers is shown in Fig. 1. The drainage layer is place over a root barrier that covers the roofing membrane. The water retention fabric is optional and the media depth and plant material vary depending on design specifications [8]. A typical green roof is constructed by placing a drainage course, growing substrate, and vegetation on top of a roof's waterproof membrane [6].

All reviewed studied showed that green roof layers consists of vegetative layer, substrate layer (soil layer), water retention fabric, filter layer, drainage layer and waterproofing layer as shown in Table 1. Many studies agree that it is the depth and type of substrate that has the major influence on green roof water retention capacity and not the vegetation type and cover [27]. Vodye et al. [29] studied the effect of two substrate depths which are 50mm and 70 mm on storm water discharge. They however found that no additional storm water benefit gain from the 70mm of substrate depth. Table 2 showed the example of thickness of extensive green roofs layers as defined by different author. The average depth of vegetative layer is from 50 to 130mm. Most of the authors are using 50mm of substrate layer and all mentions maximum depths are about 150mm in height.

Table 1: Example of green roof layers as defined by different authors

Green roof layers	References
Vegetative layer Soil layer Webbing/ geotextile filter Drainage material	Berndtsson [2]
Vegetation Growing medium Water retention fabric Filter fabric Drainage layer	Getter & Rowe [8]
Vegetation layer Substrate layer Filter layer Drainage layer Waterproofing layer	Perez et al. [15] Vodye et al. [29]

Table 2: Example thickness of extensive green roofs layers as defined by different authors

Green roof layers	Thickness, d (mm)	References
Vegetative Layer	50-130	Hathaway et al. [9]
Substrate Layer	50-150	Hathaway et al [9]
	50	Rincon et al. [16] Perez et al. [15] Shahid et al. [20] Vodye et al. [29]
	150	Sailor [18] Vijayaraghavan et al. [28]
	< 150	Beretta et al. [1] Mentens et al. [12]
	≤ 150	Carson et al. [6] Vodye et al. [29] Magill [11]
Drainage Layer	40	Perez et al. [15] Shahid et al. [20]

Substrate composition has a major impact on plant selection for green roof systems. The ideal substrate is comprised of a balance of lightweight, well-drained material, has adequate water and nutrient holding capacity, and will not break down over time. Getter & Rowe [8] mentioned that he major component of green roof substrates should be mineral-based materials such as expanded slate, shale, or clay. Other inorganic components may include sand, pumice, perlite, vermiculite, and crushed recycled clay bricks or tiles. A shallow depth will likely make root systems more susceptible to cold damage because roots are generally not as cold tolerant as the tops of plants. Despite the cultural limitations of shallow substrate depths, they are often desirable because the building must be structurally strong enough to support the added weight of the green roof. The tough species from the genus *Sedum* is the dominant vegetation type. This genus is commonly low-growing, drought tolerant, with low nutritive requirement and low biomass [11].

Wong et al. [30] found that Arachis pintoi (Perennial Peanut) can be selected as the green-roof vegetation. This evergreen perennial creeping vine is known for its hardy and vigorous growth across all seasons in this region. Green roofs in humid subtropical Hong Kong are exposed to a wide range of harsh elements, including strong winds and gusts, long and heavy rainfall, periods of drought, as well as scorching sunshine and temperatures in the summer. The plant does not reproduce by seed, it cannot spread to unintended areas through wind and birds to threaten native species [17].

2.2. Type of green roofs

Green roofs are typically divided into two main engineering categories: intensive and extensive [2]. Intensive green roofs are established with deep substrate layers, which can support larger plants and require frequent maintenance. The growing media of intensive green roofs are more than 150mm. As cited by Hathaway et al. [9] in his studies demonstrated that shallower substrate depths and steeper roof slopes resulted in greater runoff from the green roof. The thinner implementations (typically < 20 cm), known as extensive green roofs are established with thin substrate layers, supports smaller plants and typically maintenance free [3][18]. Extensive green roofs are planted with low height and slow growing plants [31]. The total depth of an extensive green roof is normally less than 150mm of growing media [1][9][10][11][12][14][16][29][30], which is much favored for retrofitting purposes compared to an extensive green roof due to being light-weight. Similarly, Carson et al. [6] found that extensive roof substrates are typically 15 cm thick or less and feature short rooting, drought resistant plants, whereas intensive roof substrates are greater than 15 cm thick and may be sowed with deeper rooting plants including shrubs and trees.

2.3. Light weight in extensive green roofs

Generally, extensive green roofs are cheaper, require less maintenance and are lighter than intensive systems. Therefore, extensive systems are implemented more frequently than intensive systems, most especially on existing building stock where rooftop weight limitations come into play. Due to their wider applicability, extensive green roofs are the focus of this study [6]. Extensive green roofs are more important from the point of view of a sustainable urban ecosystem; being lightweight they can be installed on more rooftops [11]. The most serious of all green roof failures is collapse due to insufficient support of the structure and inadequate planning of the green roof system. Weight is a crucial issue in the construction of a green roof, which can be built on an existing structure as a retrofit; therefore, before planning a green roof system, the weight limit or load must be determined. Structural engineers categorize loads from two general perspectives: dead and live loads [11]. The live weight load is the deciding factor of whether the roof will be intensive, extensive, or include elements of both systems. Green roofs are designed to withstand both live and dead loads, extensive green roof systems are evaluated while saturated that adding from 15 to 25 pounds per square foot [22].

Vodye et al. [29] fixed its target maximum wet weight somewhat arbitrarily set at 100kg/m^2 as its green roof design goal and work backward to calculate the depth of the substrate layer (i.e. 50mm). Rincon et al. [16] found that the green roofs used in the research to the conventional roof with gravel one (918 kg or 102kgm^2). In striving to find the optimum and sustainable extensive green roof design, the issue of live load in wet conditions is hence, very important. The success of the extensive green roof in mitigating storm water runoff lies on its water retention capacity and runoff dynamics.

2.4. Effect of slope on green roof storm water retention

One of the factors influencing green roof water retention capacity and runoff dynamics is the roof slope [2]. However, the different studies on slope influences on green roofs runoff retention capacity bring different results. Some studies such as Mentens et al. [12] find no correlation between roof slope and runoff, others such as VanWoert et al. [27] observes that runoff retention may depend on slope. Getter et al. [8], in his studies demonstrated that green roof slope does have an effect on runoff retention quantities. Retention values decreased as slope increased and were significant for slopes between 2% and 15% as well as between 2% and 25%. VanWoert et al. [27] with regard to slope and substrate depth, found that from all studied categories (2% - 25 mm, 2% - 40mm, 6.5% - 25mm, 6.5% - 40mm) the greatest retention percentage occurred at 2% - 40mm roof, with the least retention at 6.5% - 40mm roof. It is possible, nevertheless, that the effect of runoff retention can be seen with the influence of roof slopes coupled with other factors such as the design of green roof layers and the presence or not of different type drainage materials.

3. Benefit of green roofs

Hathaway [9] found that green roofs appear to offer a number of benefits including storm water retention, peak flow reduction of rooftop runoff, reduction of roof surface temperatures, reduction of building energy costs, extension of roof life and provision of added recreational space for residents in congested urban areas. While green roofs have been shown to provide a range of environmental benefits compared to typical impervious roofs [3][8][19][31], their ability to attenuate storm water runoff is typically the main target of existing incentive programs for their construction [6]. The benefit of implementing green roof in building construction as mention by Getter and Rowe [8] are reduced volume of storm water runoff, delayed storm water runoff, and increased life span of roofing membranes and energy conservation and the urban heat island.

4. Natural fibres and recycle waste materials in green roofs

Due to the need of sustainable practices to be implemented in construction, there are several research done on using cheap and recyclable materials for green roof building. Perez et al. [15] & Rincon et al. [16] are testing on the suitability of rubber crumbs in green roof drainage layer as an alternative to porous stones such as pumice and natural pozzolana in terms of hydrological performance and thermal reduction. Molineux et al. [13] and Cao et al. [5] studied on the potential of incorporating waste materials such as biochar (a pyrolisis product from agricultural & forestry harvest residue to urban green and manufacturing waste), crushed red brick, clay & sewage sludge, carbonated limestone and paper ash in the green roof substrate layers.

A sustainable material is made usually from natural or recycled materials and its production requires a small amount of energy. It makes limited use of non-renewable resources and has a low environmental impact. Many currently used acoustic materials cannot be considered sustainable in terms of the energy consumption and greenhouse gases emissions. Some of these materials can be harmful for human health.

Recycled materials can be regarded as an alternative to natural materials, as they contribute to lower waste production and reduced use of raw (virgin) materials. There are many examples of materials falling into this category. These include recycled rubber, plastics, textile fibers and solid wastes.

Palm oil clinker has a good ability of draining the excess water and there is no effect in term of plant development when the palm oil clinker is used as drainage layer. This indicates that there is a possibility of replacing the conventional stone materials with palm oil clinker [20].

5. Storm water mitigation

Modern approaches to storm water management strive to control the quantity and quality of urban runoff, to work in harmony with natural environmental processes to contribute to sustainable urban environments. It is best to control storm flow as close to the source as possible. When green roofs are combined with other sustainable methods of storm water mitigation, these systems can work together to be more effective than any one system by itself [23].

Climate change may further increase the highly fluctuating amount of runoff water [12]. Green roof technology has been demonstrated to reduce storm water discharge during storm events from rooftops. The reduction consists in; (i) delaying peak runoff through absorption of water by the green roof, (ii) reducing the total runoff by retaining part of the rainfall, (iii) and distributing the runoff slowly through release of the excess water that is in the substrate pores [12][23] thereby retarding peak discharge into rivers by several hours [7]. Storm water is retained by the roof membrane and taken up by plants and then gradually released through evapotranspiration back into the atmosphere. Water loads that saturate the roof membrane beyond the holding capacity escape the roof laterally through the drainage membrane and then out through drain.

Maximum run-off retention has been demonstrated as high as 88% and 44% for medium and large rain events [21]. But, there is no change in hydrology across the watershed for storm events greater than the 2-year, 24-h event [7].

Green roofs could help the urban ecosystem to mimic less disturbed watersheds. During the last two decades, a large amount of research has been published in German on the reduction of rainwater runoff for different types of roof greening. The annual rainfall-runoff relationship for green roofs is strongly determined by the depth of the substrate layer. Wide-scale green roof installation will create a more positive role in the hydrological cycle. The creation of more green areas is an answer to recent calls for more urban green space [12].

5. Conclusions

Due to their wider applicability, extensive green roofs are the focus of this study. The green roof layer for substrate is 50mm or with maximum depth of 150mm and 40mm for drainage layer. Perrenial plant and sedum are used in the vegetative layer because of the properties that is hardy and vigorous growth. Palm oil clinker has a good ability of draining the excess water and there is no effect in term of plant development when the palm oil clinker is used as drainage layer. This indicates that there is a possibility of replacing the conventional stone materials with palm oil clinker in drainage layer [20]. Perez et al. [15] and Rincon et al. [16] are testing on the suitability of rubber crumbs in green roof drainage layer as an alternative to porous stones such as pumice and natural pozzolana in terms of hydrological performance and thermal reduction. One of the factors influencing green roof water retention capacity and runoff dynamics is the roof slope [2]. However, more study needed to be done on looking into other recycled materials to be used in drainage layer and natural fibres in filter layer in replacement of non-renewable sources for storm water runoff mitigation. In striving to find the optimum and sustainable extensive green roof design, the issue of live load in wet conditions is hence, very important

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