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20.1: Research Track

SELECTING CRITERIA AND WATER PERMEABILITY MEASUREMENT OF RECYCLED AND ARTIFICIAL MATERIALS FOR GREEN ROOF LAYERS

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Abstract

European Aggregates Association Annual Review reported that the Northwestern European countries (Belgium, France, Germany, Netherlands, and the UK) produce 90% of recycled aggregates and 67% of artificial aggregates in Europe. Partially replacing the natural materials with coarse recycled and artificial materials for substrate and drainage layers of green roof systems can be considered as a viable solution to lessen the environmental impact by preserving natural resources in Northwestern Europe. On the other hand, water permeability is one of the main indicators for green roof materials. In this study, some materials available in the Northwestern European markets were selected and their water permeability was measured according to German FLL guidelines. This study also answered the question: to what extent can the water permeability be provided for the substrate and drainage layers by the inclusion of recycled and artificial materials than by conventional green roof materials? For the drainage layer, different coarse granular aggregates were suggested: Recycled Coarse Aggregate (RCA), Incinerated Municipal Solid Waste Aggregate (IMSWA) and Lightweight Expanded Clay Aggregate (LECA). The results were compared with the Natural Coarse Aggregate (NCA). For the substrate layer, the water permeability of commercial substrate materials with and without coarse recycled materials was measured and compared to each other. The results showed that NCA offered a water permeability 1.5 times higher than LECA, although the results of RCA and IMSWA did not differ significantly. Moreover, the water permeability of the substrate with and without coarse recycled materials was within the guidelines' range, indicating that they met the water passing criteria for the substrate layer.

Keywords: water permeability; recycled and artificial aggregates; green roof; substrate layer; drainage layer.

Introduction

Green roofs are a technology that is gaining popularity in urban areas because of the numerous advantages they offer. Their capacity to restore biodiversity in cities is one of these advantages

(Ishimatsu and Ito 2013; Madre et al., 2014; Sadler et al., 2011). The substrate and drainage layers of green roofs are often created with a high percentage of aggregate and a minimal amount of organic material. This eliminates additional roof weight while offering a low-nutrient growing substrate ideal for green roof vegetation (Kazemi and Courard 2020; Molineux et al., 2009; Nagase and Dunnett 2011). The addition of soil and its accompanying clay fraction can cause to reduce the water transmissivity, or an abundance of organic matter can lead to decreasing the water passing ability of the substrate layer (Snodgrass and Snodgrass 2006). To avoid the anaerobic conditions brought on by compacted soils, the aggregate component gives the growth substrate physical properties such as ideal free-draining capabilities and adequate aeration (Snodgrass and Snodgrass 2006).

The water passing ability of drainage and substrate layers of a green roof was found to be influenced by their materials' shape and type (Kazemi and Courard 2021b; Stovin et al., 2013; Szota et al., 2017; Vijayaraghavan 2016). Researchers assessed the green roof substrate layer's water permeability to make sure that it has the capacity to buffer water (Carrera et al., 2022; Graceson et al., 2014; Hill et al., 2016; Karczmarczyk et al., 2017). Concerning this, Hill et al. (2016) demonstrated that the reduced air entry pressures in the green roof due to the substrate's permeability changed the substrate layer's non-linear maximum water capacity through its depth. The water permeability of the green roof system was decreased by reducing the particle size of materials used for the substrate layer, as reported by Olszewski and Young (2011). Stovin et al. (2015) showed that the use of Lightweight Expanded Clay Aggregate (LECA) for the substrate layer enhanced the permeability and shortened the water retention time of the green roof system due to its high porosity, rounded shape, and uniform size. According to a study by Miller (2003), the water permeability and detention periods of green roof systems increased as the number of tortuous pathways for water to go through the substrate layer decreased. To improve the permeability of green roof systems, when the reservoir of the drainage layer has reached a certain level of water, any excess water should be drained away, as revealed by Brunetti et al. (2016). Low bulk density and adequate permeability are two desirable physical properties of a substrate for a green roof (Graceson et al., 2014; Hill et al., 2016). Substrate permeability is a crucial characteristic for a stormwater reduction since it affects how much rainwater runs off of green roofs (De-Ville et al., 2018). In general, the water permeability for the substrate layer of a green roof is measured according to German FLL guidelines (2018), which are widely accepted on a global scale. In the climate of the European region, The goals of these guidelines for substrate performance are most applicable to green roof technologies (Ampim et al., 2010; Dvorak 2011; Kazemi and Mohorko 2017).

The overuse of natural aggregates in the building industry has impacted the environment in recent decades, and it is estimated that the construction sector consumes around 7.5 billion tonnes of aggregates yearly (Madandoust et al., 2019; Meyer 2009; Saberian et al., 2019). These natural aggregates are commonly used for building envelopes such as green roof systems. To solve this issue, there are substitutes for natural materials that can be utilized for green roof layers, such as secondary resources like recycled and artificial materials and aggregates (Coma et al., 2014; Kazemi et al., 2021; Kazemi et al., 2022; Rincón et al., 2014). These materials' high porosity can affect the leakage of water from substrate and drainage layers and the water permeability of green roof systems. Moreover, the recycled coarse aggregates contribute to applying a lower load to the top of structures due to their lower bulk density and lighter weight, as suggested to be taken into account in the roofing configuration (Teemusk and Mander 2009).

Kazemi et al. (2021a; 2021b; 2022) have already assessed the thermal resistance of green roof layers (substrate and drainage layers), including different coarse recycled materials, where the Rc-value was assumed as a thermal resistance indicator (Kazemi et al. 2021). The impact of commercially available substrates on hydrolytic characteristics has already been studied by researchers (Bengtsson 2005; Berretta et al., 2014; Morgan et al., 2013; Volder and Dvorak 2014). It is also worthy to evaluate the water permeability of alternate recycled and artificial materials for use in green roof layers (Mickovski et al., 2013; Molineux et al., 2009; Kazemi and Courard 2021a). A recent study was proposed by Kazemi et al. (2022): it considered the water permeability as another indicator, and assessed the water draining ability of different recycled and artificial materials for substrate and drainage layers of roofing systems. The results have been taken into account in this paper.

Materials and Method

According to the availability of commercial materials in Northwestern European countries, some criteria were assumed to choose recycled and artificial materials for the substrate and drainage layers of green roof systems. The water permeability was measured and the German FLL guidelines (2018), providing performance standards for building green roof systems, were used to control the substrates' water permeability values. In addition to this, the two-sample t-test method (t_{test}) was used according to ISO 3301 (1975) to compare the results of water permeability of different materials together.

Screening and Selecting the Tested Materials

According to the European Aggregates Association Annual Review (UEPG 2021), it is estimated that 273 and 63 million tons of recycled and artificial aggregates have been produced respectively by European countries. Northwestern European countries (Belgium, France, Germany, Netherlands, and the UK) have accounted the highest amount of production: 248.4 million tons of recycled aggregates and 42.4 million tons of artificial aggregates (90% of recycled aggregates and 67% of artificial aggregates in Europe).

Since the recycled and artificial aggregates could be used for the drainage and substrate layers of green roof systems, this study only focused on these aforementioned layers. Some criteria were taken into account to choose materials for the drainage and substrate layers: commercial materials, high porosity, lightweight, recycling, and artificial productions. After that, for each layer, the water permeability of suggested materials was compared with that of the control material for that layer. Considering this, three types of coarse recycled and artificial aggregates were chosen for the drainage layer: Recycled Coarse Aggregate (RCA), Incinerated Municipal Solid Waste Aggregate (IMSWA), and Lightweight Expanded Clay Aggregate (LECA). The results of aforementioned coarse aggregates for the drainage layer were compared to the

Natural Coarse Aggregate (NCA) as a control granular coarse aggregate. The size of coarse aggregates was about 7 mm.

For the substrate layer, the Zinco substrate containing organic matter, recycled bricks, and tiles (SP) was selected. The result of SP was compared to the substrate without coarse recycled materials (SC) as a control soil.

Material Characteristics

The properties of the substrate and drainage layers' materials (Table 1). The properties of other materials were measured by Kazemi et al. (2021a; 2021b; 2022a; 2022b). The ratio of the volume of void spaces and pores in dry materials to the overall volume is known as porosity. Also, Kazemi et al. (2021a; 2021b; 2022a; 2022b) described how the water absorption coefficient of green roof layers' materials could be determined following the EN 1925 (1999), respectively.

Table 1. Properties of substrate and drainage layer materials.

Materials ID	SC	SP	NCA	RCA	IMSWA	LECA
Density (kg/m^3)	1075	1001	1437	1165	1147	439
Porosity (%)	48.2	48.63	41.67	49.56	47.26	55.08
Water absorption coefficient (kg/m^2.s$^{0.5}$)	-	-	0.026	0.072	0.067	0.107

Water Permeability Measurement

The water permeability was evaluated in accordance with ISO 17892-11 (2019) for evaluating the capacity of green roof materials to drain water. The water permeability values of the materials were measured, and those for substrates were controlled in accordance with German FLL guidelines (2018). According to German FLL guidelines (2018), the substrate layer of a green roof should have a water permeability between 10^{-5}-1.17×10^{-3} m/s. Moreover, the materials were submerged in water continuously for 24h up to the testing date.

To obtain the water permeability (k) of materials, Eq. (1) was used:

$$k = \frac{Q}{A} \times \frac{L}{\Delta h} \tag{1}$$

where Q is the flow rate in m^3/s, A is the cross-sectional of specimen in m^2, L is the specimen's length in m, and Δh is the water head difference between the water level in the reservoir and that out of specimen in m.

The results were the average of three specimens, so the standard deviation (SD) value for each specimen was calculated in order to evaluate the scatter of the data. It was necessary to determine for each layer if the suggested materials had the same water permeability as the control material or not. Therefore, the outcome of the substrate with coarse recycled materials (SP) and the control substrate without coarse recycled materials was compared (SC). Also, IMSWA, RCA, and LECA's water permeability value for the drainage layer was compared to that of the coarse control aggregate (NCA).

According to ISO 3301 (1975), the two-sample t-test method (t-test) was employed to determine whether or not the unknown population means of two materials are equal. To compare the mean values of two materials, this method can take sample size (n) and standard deviation (SD) into account (Daya 2003; Gönen et al. 2005).

The pooled standard deviation (S_p), which may be determined using Eq. (2), can be used to estimate the standard deviation of the two materials together.

$$S_p^2 = \frac{((n_1-1)SD_1^2)+((n_2-1)SD_2^2)}{n_1+n_2-2} \tag{2}$$

where n_1 and n_2 represent the number of materials from the first and second groups whose findings were used to calculate their standard deviation (SD_1 and SD_2).

Eq. (3) can be used to calculate the value of t_{test}:

$$t_{test} = \frac{Difference\ of\ two\ materials'\ averages}{Standard\ error\ of\ difference} = \frac{(\bar{x}_1-\bar{x}_2)}{S_p\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}} \tag{3}$$

where the average values for the first and second groups of materials are $\bar{x}_1$ and $\bar{x}_2$, respectively.

Considering a 95 percent confidence level (α = 0.05), the t-value was taken from the t_{test} table provided in ISO 3301 (1975) in order to compare the test statistic to the outcome of the t-test method. The degrees of freedom (d_f) were derived using Eq. (4):

$$d_f = n_1+n_2-2 \tag{4}$$

The mean of the suggested materials and the reference material can be taken to be equal with a 95% confidence level when the results of the t-test method for two materials are smaller than the t value extrapolated from the t_{test} table. In any other case, there is a difference between the means of the two.

Results

Physical Characteristics of Materials for Green Roof Layers

A comparison of porosity and density of substrate and drainage materials for green roof systems (Figure 1). Regarding porosity, for the drainage materials, the results of 41.67 percent, 47.26 percent, 49.56 percent, and 55.08 percent were obtained for NCA, IMSWA, RCA, and LECA, respectively. So, the highest and lowest porosities were obtained for the LECA and NCA, respectively. Within the limits of porosity specified for the sandy surface soils (35 percent – 50 percent) and finer textured soil (40 percent - 60 percent) (Hao et al. 2008), SC and SP's porosities of 48.2 percent and 48.63 percent, respectively, were compatible and there was no discriminant difference between the substrate porosity with and without coarse recycled materials (48.63% vs. 48.2%).

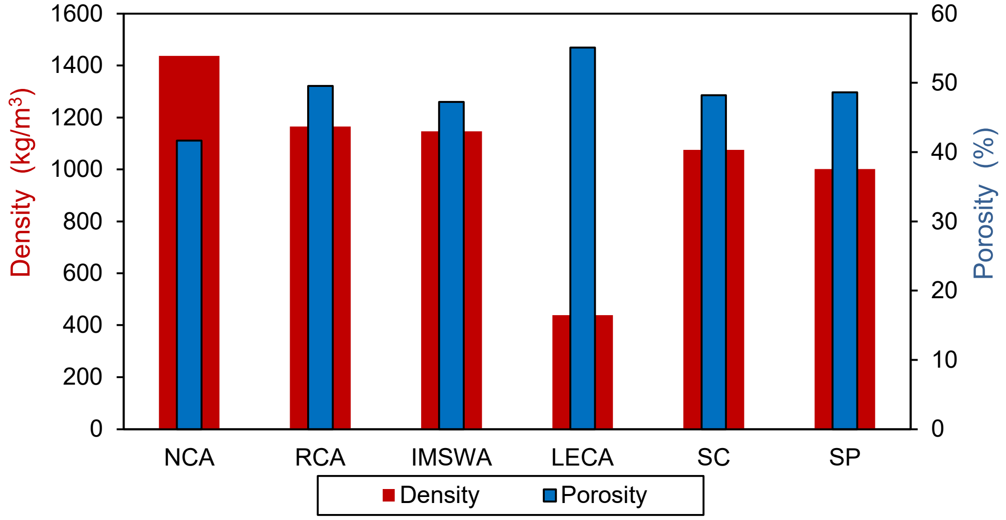

Figure 1. Density and porosity of materials.

According to the results, NCA, IMSWA, RCA, and LECA had coarse granular aggregates with densities of 1436.56, 1147.26, 1164.47, and 439.35 kg/m^3, respectively. Therefore, contrary to the results of porosity, the highest and lowest densities were obtained for the NCA and LECA, respectively. For the substrate layer, the SC's density was roughly 10% higher than that of SP.

Water Permeability Results

The water permeability values for the drainage and substrate materials (Figure 2). The water permeability of granular aggregates such as NCA, IMSWA, RCA, LECA, SC, and SP was, respectively, about 3.8×10^{-3}, 4.3×10^{-3}, 4.1×10^{-3}, 2.5×10^{-3}, 2.6×10^{-5} and 1.7×10^{-5} m/s. Their respective standard deviation (SD) values were 3.42×10^{-4}, 4.86×10^{-4}, 1.15×10^{-4}, 6.2×10^{-6}, 8.7×10^{-7}, and 3.6×10^{-7}, respectively.

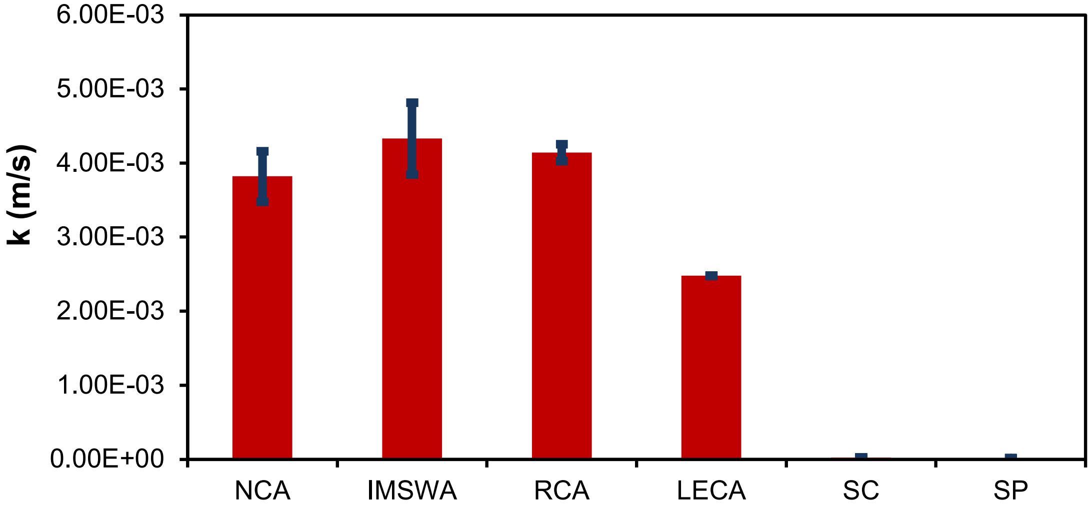

Figure 2. Water permeability.

The analysis of the water permeability test using the two-sample t-test method is shown in Table 2 and is derived using Eq. (3): IMSWA, RCA, and LECA t_{test} values of 1.487, 1.536, and 6.785, respectively, were obtained in comparison to NCA. Compared to SC, the corresponding value for SP was 15.855.

Since n_1 and n_2 added up to 6, and the results were the average of three samples, d_f was equal to 4 using Eq. (4). From the t_{test} table, the t value was taken out, and it was found to be 2.132 with a 95% confidence level. The t_{test} result for SP (15.855) was higher than 2.132, showing that the mean water permeability for SC was higher than that for SP. The t_{test} results for IMSWA and RCA (1.487 and 1.536) were less than 2.132, as shown in Table 2, suggesting that their water permeability was similar to NCA. The t-test value between LECA and NCA, however, was 6.785 and was higher than 2.132. It means that LECA and NCA had different behaviors.

Table 2. Results for the water permeability test using the two-sample t_{test} method.

Materials	NCA	IMSWA	RCA	LECA	SC	SP
t_{test}	-	1.487	1.536	6.785	-	15.855

Discussion

The results of the t_{test} method showed that even though the aggregate types varied, IMSWA and RCA's water permeability means were the same as those of the NCA: more than the coarse aggregates' type, air voids between the aggregates were determinant their water permeability performance. Considering that the water permeability of the aforementioned materials was nearly the same, it is recommended to use IMSWA and RCA for the drainage layer as the use of these recycled materials are more economical and can decrease the burden on the environment by reducing the natural resource extractions.

According to the results, there was a difference in the water permeability between NCA and LECA, as indicated by the t_{test} method's result between the two (6.785). The water permeability between the NCA (3.8×10^{-3} m/s) was roughly 1.5 times greater than that of LECA (2.5×10^{-3} m/s). Compared to NCA (41.67%), LECA has a higher porosity (55%). Moreover, compared to the NCA, which was made of crushed coarse materials, LECA was made of rounded expanded clay aggregates. Consequently, LECA's water permeability performance was lower than that of NCA. It can be due to physical characteristics and the rounded shape of LECA, resulting lower water passing ability for the drainage layer of green roof systems.

The substrate layer of the green roofs was adequately able to transmit water thanks to the soil materials (SC and SP), as the water permeability of SC and SP was found to be 2.6×10^{-5} and 1.7×10^{-5} m/s, respectively, which was within the limit specified by FLL guidelines (2018). The findings of the t_{test} demonstrated that the mean water permeability for SC was higher than that for SP, with values of 2.6×10^{-5} and 1.7×10^{-5} m/s, respectively. The former had a water permeability almost 1.5 times greater than the latter. The porosity of SC (48.2 percent) and SP did not differ significantly (48.63 percent). As Miller (2003) discovered, the difference can be attributed to resource of coarse recycled materials for SP, which provided tortuous channels for water to pass through the substrate layer and subsequently reduce the green roof systems' water passing ability. Because of this, in SC, the water may easily pass through the fine soil particles. However, the SP prohibited easily moving water through the substrate layer by partially replacing these fine particles with coarse recycled materials. As a result, SC had a higher permeability.

Conclusions

This study compared the physical characteristics and permeability of the green roof layers made of various recycled and artificial aggregates. Based on the results of the experiment, the following conclusions can be made:

- Among different coarse granular aggregates for drainage layers, the lowest density and highest porosity were obtained with Lightweight Expanded Clay Aggregate (LECA).
- The t-test method showed that SC had water permeability almost 1.5 times greater than SP. The SC fared better than the SP at allowing water to penetrate through the substrate layer. However, the water permeability values for SC and SP fell within the permitted range and they gave the substrate layer of green roofs a necessary water passage ability.
- IMSWA and RCA performed almost identically to the NCA in terms of water permeability. Therefore, rather than the coarse particles, the voids between the aggregates were determinant for water permeability porosity.

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