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Water permeability, water retention capacity, and thermal resistance of green roof layers made with recycled and artificial aggregates

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ABSTRACT

Substituting natural aggregates in the green roof substrate and drainage layers with lightweight artificial and recycled coarse materials is an eco-friendly alternative for applying lower load to the rooftops and preserving natural resources. However, a lack of precise understanding of the thermal resistance, water passing ability, and water holding capacity of green roof materials, including recycled and artificial materials, has raised a demand for measuring their Rc-value, water permeability, and water retention capacity as three main indicators for green roof systems. This study comparatively evaluated the thermal resistance, water permeability, and water retention capacity of green roofs with substrate and drainage layers, including coarse recycled and artificial materials. Different kinds of coarse granular aggregates were separately used for the drainage layer, including Natural Coarse Aggregate (NCA), Recycled Coarse Aggregate (RCA), Incinerated Municipal Solid Waste Aggregate (IMSWA), and Lightweight Expanded Clay Aggregate (LECA). The substrate layers were made with coarse recycled materials (SC) and without coarse recycled materials (SP) in wet and dry states. The outcomes revealed the highest thermal resistance and the lowest weight were obtained for 20-cm green roofs with a 15-cm substrate layer and 5-cm drainage layer of LECA. The water permeability of NCA was obtained 1.5 times more than that of LECA, whereas there was no significant difference between the result of the former, RCA, and IMSWA. The water retention capacity of the LECA was two times higher than that of the NCA. SC and SP satisfied the water passing and retention criteria given for green roofs.

1. Introduction

Sustainable urban drainage systems have been increasingly developed for building envelopes such as rooftops to improve the energy efficiency of houses and reduce the high volume of runoff during stormwater events [1–10]. As a sustainable ecosystem system, the green roof is known for its ability to provide thermal resistance for rooftops in some cases and buffer the surface stormwater runoff in urban areas [11–18]. The shape and type of materials used in green roof drainage and substrate layers significantly impact energy efficiency and rooftop water evacuation [19–22].

The German FLL guidelines [23] are internationally recognized and widely used to measure the water permeability (estimating drainage) for the green roof substrate layer. These guidelines' targets for substrate performance are most relevant to green roof technologies in the European region's climate [24–26]. Regarding the water buffering capability, Kaczmarczyk et al. [2] revealed that the water permeability depended on the porosity and shape of the materials used for the green roof substrate layer. Another study by Wong and Jim [27] revealed that using high porous materials such as rock wool for the substrate layer increased the porous nature and permeability of green roof systems. Ouldboukhitine et al. [11,28] measured the hydrological properties of the green roof components. According to the results, the green roof substrate's permeability was gained five times more than that of concrete materials owing to the higher porosity of the former (55.13%) than the latter (19.07%). Miller [29] demonstrated that increasing the number of tortuous paths for passing water through the substrate layer caused to increase in the detention times and decrease the water permeability of green roof systems. Stovin et al. [30] assessed the hydrological performance of different types of green roof substrates. As per the results, the rounded shape, high porosity, and uniformly-size LECA resulted in the most increased permeability and the lowest water detention time for the substrate layer.

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Abbreviations

LECA	Lightweight Expanded Clay Aggregate
NCA	Natural Coarse Aggregate
RCA	Recycled Coarse Aggregate
IMSWA	Incinerated Municipal Solid Waste Aggregate
SP	Substrate with course recycled materials (Proposed Substrate)
SC	Substrate without course recycled materials (Control Substrate)
SD	Standard Deviation

Another important indicator for green roof materials is the water retention capacity of substrate materials, which has been taken into account by different green roof guidelines and standards, such as the German FLL guidelines [23]. Since extensive green roofs require less maintenance and have shallower green roof layers, growing different types of plants and species is highly dependent on substrate and drainage layers [23,31]. In order to impose a lower load on buildings, the substrate layer should not be deeper than 20 cm. Hence, the maximum yearly water retention for green roof systems is approximately 65% [23]. Over the range of substrate depths associated with green roofs, substrate composition probably has a higher impact on a green roof's capacity to retain water than substrate depth does [23]. Therefore, without considerably increasing the weight of green roofs, the substrate composition in green roof layers may be able to boost the green roof's ability to hold more water [32].

Moreover, the materials used for the drainage layer can participate in increasing the water retention capacity of green roof systems. Ngan [33] demonstrated that the crushed brick, as a lightweight porous material, reduced pressure on the substrate and drainage layers while enhancing the green roof system's ability to retain water. Coma et al. [34,35] showed that using more porous materials, like crushed bricks and pozzolana (porous volcanic gravel), might be a promising strategy to increase the drainage layer's ability to absorb water. Eksi and Rowe [36] used recycled crushed porcelain as a component of green roof substrates. The results revealed that reducing the recycled crushed porcelain particle size could probably lead to increasing the water retention capacity of the substrate layer. Yang et al. [37] showed that using coarse biochar increased the water retention capacity and reduced the weight of green roof substrate layer.

The green roof layers' heat resistance capability depends on their thickness and material type [4,5,38]. Researchers have praised different kinds of materials' impact on the performance of green roof layers [39]. Concerning this, Parizotto and Lamberts [40] constructed a green roof's drainage layer using natural gravel aggregates, which effectively reduced the daily temperature fluctuation and slowed down the heat transfer conduction. Almeida et al. [41] demonstrated that the substrate layer boosted the thermal insulation of green roof systems; however, in a wet state, its insulating capability was not as high as in a dry state. He et al. [42] revealed that increasing the substrate's water content boosted the cooling impact of the green roof. Furthermore, when the green roof was employed for the rooftops, the cooling and heating loads of the structures dropped. Fabiani et al. [43] found that the water content had a noticeable impact on the thermal characteristics of the green roof layers, where it caused to increase in the substrate's thermal conductivity by three times on rainy days.

Natural mineral and energy resources are heavily utilized to construct building envelope components (such as roofing systems) and provide adequate indoor thermal comfort [22,44–53]. For instance, consuming an estimated 40% of primary energy for construction sectors has produced a series of insoluble environmental concerns [54,55]. Since the rooftop is one of the main sources of energy loss, partially replacing natural components with recycled and artificial coarse materials in green roof layers with adequate thermal resistance can help to address these environmental issues [5,34,35,56,57]. Regarding this, the green roof's drainage layer was constructed by Coma et al. [34,35] using pozzolana and rubber crumbs, and its performance was assessed in the Mediterranean environment. According to the findings, the green roof's poor thermal efficiency was developed in winter with increased drainage and substrate layers' depth. Cascone et al. [58] compared the thermal resistance of three different granular drainage materials: perlite, expanded clay and rubber crumb. The results showed that the highest values of thermal conductivity were obtained for the rubber crumb. Also, Cascone [59] revealed that, compared to the non-insulated conventional roof, the extensive green roof with recycled rubber had a much lower environmental impact. To analyze the thermal resilience of the same roofing system with pozzolana and rubber crumbs, Kazemi et al. [4,5] modeled temperature fluctuations within its layers. The findings showed that the increment of the substrate and drainage layers' thickness improved the roofing system's thermal efficiency, despite the effects of thicker layers being the same. In 2021 and 2022, Kazemi et al. [22,60] assessed how the green roof with a 15 cm-substrate of coarse recycled materials and a 5-cm drainage layer of recycled coarse aggregates was able to resist the heat-flow in which the R-value as a heat resistance indicator was measured for green roof layers in accordance to ISO 9869-1 standard [61]. As per the results, the Rc-value of green roof layers with and without coarse recycled materials was near to each other. Also, Kazemi et al. [12] assessed the thermal resistance of green roofs with a 15 cm-substrate of coarse recycled materials and a 5-cm drainage layer of incinerated municipal solid waste aggregates and compared the results of a dry substrate with a wet substrate. As per the results, the heat transfer decreased through the green roof substrate with air voids in dry state.

In this context, it is clear that some studies have been done on the heat flow measurement of layers, including coarse recycled materials for green roofs, where the Rc-value was assumed as a heat resistance indicator [61]. However, more research is mandatory to measure the other artificial materials' thermal resistance for the green roof drainage and substrate layers and compare their results to each other. On the other hand, since water permeability and water retention capacity are other critical indicators for green roofs [23], the coarse recycled and artificial materials' water permeability and water holding capacity need to be measured. Therefore, in this research, a comparative study on thermal resistance of different granular materials as the green roof drainage layer was performed in which the Rc-value of green roof with a dry and wet substrate including coarse recycled materials and the drainage layer of LECA was measured in accordance to ISO 9869-1 standard [61]. Then, the results were compared with those given by Kazemi et al. [12,22,60] for the green roof system with the same substrate but with drainage layers made up of other granular coarse aggregates. The water drainage and water holding capacity of commercial substrate and drainage materials including coarse recycled and artificial aggregates were also measured.

2. Materials and methods

Considering that, in Europe, 90% of recycled aggregates and 67% of artificial aggregates are produced in Northwestern European countries (Belgium, France, Germany, Netherlands, and the UK) [62], this study mainly focused on substrate and drainage layers of green roof systems in which coarse recycled and artificial materials could be used. Therefore, the coarse recycled and artificial materials were considered independent variables in this study and were chosen for the substrate and drainage layers according to some selection criteria. After that, three leading indicators as dependent variables were measured and analyzed for green roof systems: Rc-value as heat resistance indicator, water permeability as water drainage indicator, and water retention capacity as water holding indicator.

2.1. Selection criteria and screening of tested materials

This study considered some criteria for selecting materials for the green roof layers: lightweight, high porosity, availability in the market, recycling, and artificial production, as presented in Table 1. Concerning this, the Zinco substrate, including recycled tiles, bricks, and organic matter, was considered for the substrate layer in dry and wet states (SP_Dry and SP_Wet), similarly to what was used by Kazemi et al. [12,22,60]. This lightweight substrate, including coarse recycled materials, was commercially available for extensive green roof systems in Northwestern Europe. The substrate without course recycled materials in dry and wet states (SC_Dry and SC_Wet) was used for the control substrate layer.

Different granular coarse aggregates available in the market were suggested for the drainage layer according to the selection criteria: Recycled Coarse Aggregate (RCA), Incinerated Municipal Solid Waste Aggregate (IMSWA), and LECA. The RCA and IMSWA were classified as recycled coarse aggregates. LECA was a coarse artificial aggregate chosen for the drainage layer owing to its lightweight and high porosity [48,57,63,64]. Natural Coarse Aggregate (NCA) was considered as a control coarse granular aggregate for the drainage layer. It is noteworthy that the possibility of using other aggregates like coarse crushed brick aggregates for the drainage layer was also assessed in this study. However, the coarse crushed brick aggregates without contamination were not commercially available in Northwestern Europe.

2.2. Materials' characteristics

Green roof materials' properties are presented in Table 2. LECA's characteristics were measured in this study. The corresponding attributes for other materials were determined by Kazemi et al. [12,22,60]. Specific heat capacity, water vapor diffusion resistance factor, and water absorption coefficient of materials were measured according to standards ASTM D4611-16 [65], EN 1015 [66], and EN 1925 [67], respectively, as explained in detail by Kazemi et al. [22,60]. Porosity is the volume of void spaces and pores of materials to the total volume (volume of void spaces, materials, and their pores) as determined by Kazemi et al. [12,22]. The materials' ability to hold water is their free water content. Indeed, with a relative humidity of 100%, this characteristic is determined by the materials' capillary action, trapping the water molecules within their pore structure [22,68]. Reference water content is the sorption moisture corresponding to a relative humidity of 80% [69]. More details about the free and reference water content of materials were presented by Kazemi et al. [12,22].

2.3. Rc-value measurement (heat resistance indicator)

Fig. 1 shows the configuration of green roof layers to measure their thermal performances. Rc-value, as the rate of transfer of heat through a building element either a single material or a composite, was used for heat flow measurement and analysis [61]. This study constructed 15- and 5-cm moulds to measure the thermal resistance of substrate and drainage layers, respectively (Figs. 1(a) and 2(b)). A 20-cm mould was also made to measure the substrate and drainage layers' thermal resistance simultaneously (Fig. 1(c)). The temperatures were applied to each mould's top and bottom using a thermal device. After that, the Rc-value of each specimen was obtained based on the criteria given by ISO 9869-1 standard [61]. Kazemi et al. [12,22,60] presented the detailed criteria for green roof layers' heat flow measurement specified by ISO 9869-1 standard [61]. They also optimized the substrate and drainage layers' thickness using modelling outputs.

The green roof specimens' component details and thicknesses are presented in Table 3. For all coarse granular aggregates as the drainage layer, a size of 7 mm was selected. The Rc-value of the 5-cm drainage layer of LECA (LECA5) was measured in this study. After that, Rc-values of green roofs with a 5-cm drainage layer of LECA and a 15-cm wet and dry substrate layer with coarse recycled materials (LECA5-SP15_Wet and LECA5-SP15_Dry) were determined, and the results were compared with those given by Kazemi et al. [12,22,60] for the green roof layers made up of other materials. Kazemi et al. [22,60] considered a 5-cm natural coarse aggregate drainage layer and a 15-cm wet and dry substrate layer with no coarse recycled materials (recycled tiles and bricks) as the reference green roofs (NCA5-SC15_Wet and NCA5-SC15_Dry).

2.4. Water permeability (water drainage indicator)

As a key indicator for assessing the water draining ability of green roof materials, the water permeability was measured according to standard ISO 17892-11 [70]. The materials' water permeability values were obtained, and those for substrates were controlled using the German FLL guidelines [23], providing performance criteria for constructing green roof systems. The materials were immersed for 24 h in water until the date of testing as recommended by the German FLL guidelines [23]. Note that the water permeability of the green roof's substrate layer should be in the range of 10^{-5}-1.17×10^{-3} m/s as recommended by FLL guidelines [23].

Fig. 2 shows a cross-sectional view of the permeability test, in which 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 the specimen in m. The discharge velocity, v, (m/s) can be calculated using Eq. (1):

$$v = \frac{Q}{A} \tag{1}$$

where Q is the flow rate in m^3/s, and A is the cross-sectional specimen in m^2.

Eq. (2) was used for calculating the hydraulic gradient (i):

$$i = \frac{\Delta h}{L} \tag{2}$$

Considering Eqs. (1) and (2), in this study, the water permeability (k) was obtained using Eq. (3):

$$k = \frac{v}{i} = \frac{Q}{A \times i} = \frac{Q}{A} \times \frac{L}{\Delta h} \tag{3}$$

To assess the scatter of the data, the standard deviation (SD) value for each specimen was obtained, where the results were the average of three specimens. For each layer, it was required to assess whether the proposed materials had the same water permeability as the reference material. For the drainage layer, the mean of water permeability for IMSWA, RCA, and LECA was compared with that of the coarse control aggregate (NCA). For the substrate layer, the result of the substrate with

Table 1
Selection criteria for green roof materials.

Selection Criteria				Lightweight	High porosity	Commercial production	Recycled material	Artificial material
Materials	Substrate layer	Control	SC_Wet& SC_Dry	–	–	✓	–	–
		Suggested	SP_Wet & SP_Dry	✓	✓	✓	✓	–
	Drainage layer	Control	NCA	–	–	✓	–	–
		Suggested	RCA	✓	✓	✓	✓	–
			IMSWA	✓	✓	✓	✓	–
			LECA	✓	✓	✓	–	✓

Table 2
Green roof materials' properties.

Materials	Density (kg/m³)	Porosity	Specific heat capacity, Dry (J/kg K)	Water vapor diffusion resistance factor	Reference water content (kg/m³)	Free water content (kg/m³)	Water absorption coefficient (kg/m².s^0.5)
SC_Wet [22]	1075	0.48	–	–	10.31	380.95	–
SP_Wet [22]	1001	0.486	–	–	7.73	285.71	–
SC_Dry [60]	856	0.48	880	3.62	–	–	0.47
SP_Dry [60]	944	0.47	810	3.35	–	–	0.22
NCA [22]	1437	0.42	770	1	1.16	42.86	0.03
RCA [22]	1165	0.50	730	1	3.32	122.76	0.07
IMSWA [12]	1147	0.47	750	1	2.74	101.2	0.07
LECA	439	0.55	710	1	2.83	141	0.11

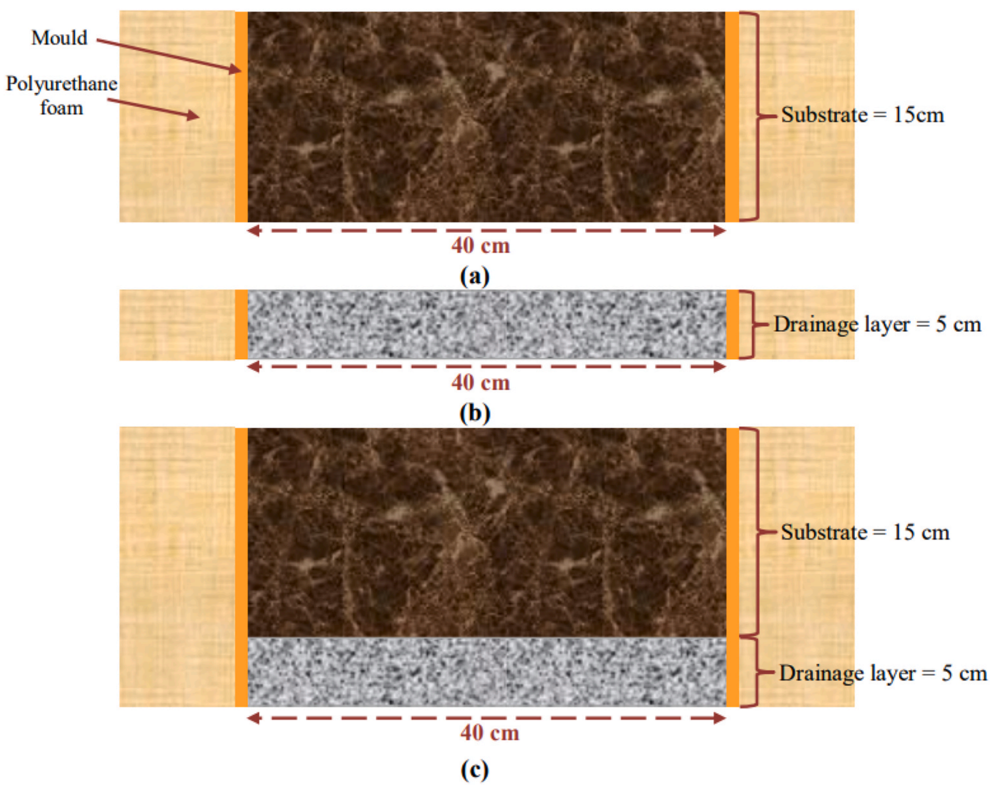

Fig. 1. Schematic representations of 15-cm mould for substrate layer (a); 5-cm mould for drainage layer (a); 20-cm mould for a green roof with substrate and drainage layers (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

coarse recycled materials (SP) was compared with the reference substrate without coarse recycled materials (SC). Concerning this, the two-sample *t*-test method (t_{test}) was used in accordance with ISO 3301 [71], which is suitable for assessing whether two materials' unknown population means are equal or not. Indeed, this method can consider the sample number (n) and SD of two materials to compare their mean values [72,73]. To make a combined estimate of the two materials' standard deviations, the pooled standard deviation (S_p) can be calculated using Eq. (4):

$$S_p^2 = \frac{\left((n_1 - 1)SD_1^2\right) + \left((n_2 - 1)SD_2^2\right)}{n_1 + n_2 - 2} \quad (4)$$

where n_1 and n_2 are the number of first and second groups of materials whose results were used to obtain their standard deviation (SD_1 and SD_2).

The value of t_{test} can be calculated using Eq. (5):

$$t_{test} = \frac{Difference\ of\ two\ materials'\ averages}{Standard\ error\ of\ difference} = \frac{(\bar{x}_1 - \bar{x}_2)}{S_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \quad (5)$$

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

To compare the test statistic to the *t*-test method's result, the degrees of freedom (d_f) were obtained using Eq. (6), and the t value was extracted from the t_{test} table given in ISO 3301 [71] with the assumption of 95% confidence (α = 0.05).

$$d_f = n_1 + n_2 - 2 \quad (6)$$

When the *t*-test method's result for two materials is less than the t value extracted from the t_{test} table, the mean of the proposed materials and the reference material can be considered the same with 95% confidence. Otherwise, there is a difference between the mean of the former

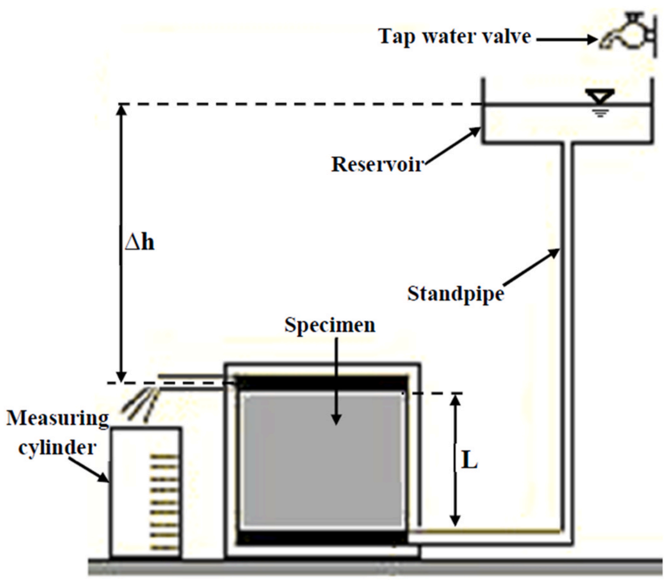

Fig. 2. Schematic representation of water permeability test.

and the latter.

2.5. Water retention capacity (water holding indicator)

The water retention measurement of green roof materials was carried out according to FLL guidelines [23], where this indicator's range for the substrate materials should be within 35% and 65%. Fig. 3 shows the apparatus used for the water retention capacity test. The results were the average of three specimens. Therefore, three steel frames with 150 mm diameter and 165 mm height were used for molding each type of material. As recommended by FLL guidelines [23], the substrate materials were compacted in three layers using the proctor hammer, where a 4.5 kg hammer was dropped 6 times from 450 mm height onto the surface of each layer, and molded into steel frames. However, since dropping the hammer caused to break of the coarse granular aggregates of the drainage layer, they were not compacted using the proctor hammer. Instead of it, the coarse aggregates for the drainage layer were shaken and compacted using a shaker table. After the material compaction, the steel frames were immersed in baskets of water and taken out after 24 h. Then, the water hose (Fig. 3) was used to drain the water for 2 h as recommended by FLL guidelines [23]. Note that the top and bottom of steel frames were covered using stainless steel wire meshes with a size of 0.6 mm to prevent fine washing particles out. Thereafter, the materials were dried and kept in the oven at 105 °C until achieving a constant weight. To analyze the results of the water retention capacity test, the two-sample *t*-test method (t_{test}) was used according to ISO 3301 [71], similar to the water permeability test.

3. Results

3.1. Green roof materials' physical properties

Green roof materials' properties are presented in Table 2. As per the results, the density of the SC was about 10% more than that of the SP, either in the wet state or in dry state. The density of coarse granular aggregates, including NCA, IMSWA, RCA, and LECA was 1437, 1147, 1165, and 439 kg/m^3, respectively. Therefore, the drainage layer with LECA had the lowest weight in comparison to other coarse granular aggregates layers used for green roof systems.

The soil porosity is dependent on the arrangement and texture of solid soil [29,30,74–77]. For example, the typical range of porosity of soil for sandy surface soils is between 35% and 50%, while the corresponding value for finer textured soil is between 40% and 60% [74]. In this study, the porosities of SC and SP were obtained at 48.2% and 48.63%, respectively, which were within the ranges of porosity given for the sandy surface soils (35%–50%) and finer textured soil (40%–60%) [74]. Furthermore, comparing the porosity of SC and SP showed that no significant difference was observed between substrate porosity without coarse recycled materials (48.2%) and coarse recycled materials (48.63%). Concerning the coarse granular aggregates' porosity, the values of 41.67%, 47.26%, 49.56%, and 55.08% were obtained for NCA, IMSWA, RCA, and LECA, respectively, demonstrating that LECA was the most porous aggregates for the drainage layer.

The water absorption coefficient of the SC (0.47 kg/m^2.s$^{0.5}$) was about twice more than that of the SP (0.22 kg/m^2.s$^{0.5}$). The free water content of the former (380.95 kg/m^3) was about 33% more than that of

Table 3
Details of green roof layers.

Specimens ID	Type of materials			Thickness (cm)		Substrate state
	Drainage layer	Substrate		Drainage layer	Substrate	
		Without coarse recycled materials	With coarse recycled materials			
NCA5 [22]	Natural coarse aggregate	–	–	5	–	–
RCA5 [22]	Recycled coarse aggregate	–	–	5	–	–
IMSWA5 [12]	Incinerated municipal solid waste aggregate	–	–	5	–	–
LECA5	Lightweight expanded clay aggregate	–	–	5	–	–
SC[a]15_Wet [22]	–	✓	–	–	15	Wet
SC15_Dry [60]	–	✓	–	–	15	Dry
SP[b]15_Wet [22]	–	–	✓	–	15	Wet
SP15_Dry [60]	–	–	✓	–	15	Dry
NCA5-SC15_Wet [22]	Natural coarse aggregate	✓	–	5	15	Wet
NCA5-SC15_Dry [60]	Natural coarse aggregate	✓	–	5	15	Dry
RCA5-SP15_Wet [22]	Recycled coarse aggregate	–	✓	5	15	Wet
RCA5-SP15_Dry [60]	Recycled coarse aggregate	–	✓	5	15	Dry
IMSWA5-SP15_Wet [12]	Incinerated municipal solid waste aggregate	–	✓	5	15	Wet
IMSWA5-SP15_Dry [12]	Incinerated municipal solid waste aggregate	–	✓	5	15	Dry
LECA5-SP15_Wet	Lightweight expanded clay aggregate	–	✓	5	15	Wet
LECA5-SP15_Dry	Lightweight expanded clay aggregate	–	✓	5	15	Dry

[a] Substrate with no coarse recycled materials.
[b] Substrate with coarse recycled materials.

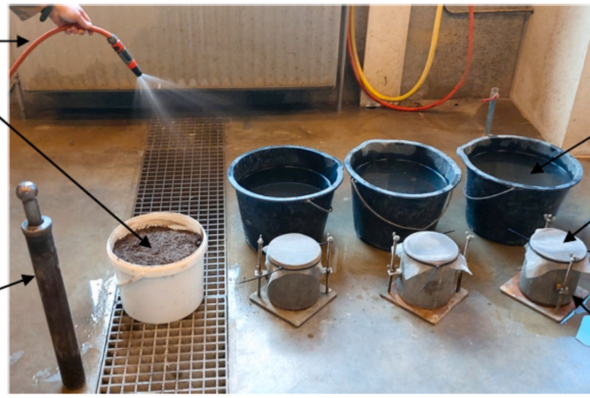

Fig. 3. Apparatus used for the water retention capacity test.

the latter (285.71 kg/m^3). The water absorption coefficients for coarse granular aggregates of NCA, IMSWA, RCA, and LECA were 0.03, 0.07, 0.07, and 0.11 kg/m^2.s$^{0.5}$, respectively. Therefore, the highest value was obtained for LECA as the drainage layer's granular aggregate. This was also observed for the free water content results, where the values of 42.86, 101.2, 122.76, and 141 kg/m^3 were obtained for NCA, IMSWA, RCA, and LECA, respectively. So, LECA had the greatest water holding capacity compared to other coarse granular aggregates.

3.2. Rc-value

The green roof layers' heat flow measurement results are presented in Table 4. To ensure that the data was valid and reliable, the Rc-values needed to be assessed during the convergence time, which should be considered at least 72 h as recommended by ISO 9869-1 [61]. According to Rc-values in convergence time, less than a 3.9% difference was detected between the first and final 67% of data. The discrepancy between data collected 24 h before the end of the heat flow measurement and data collected at the end of the test was no more than 2.4%. Based on the criteria given by standard ISO 9869-1 [61], the differences above should not be more than 5%.

According to the heat flow measurement results, Rc-values were obtained at about 0.44 m^2 K/W for all 5-cm drainage layers (NCA5, RCA5, and IMSWA5), except for LECA5 (0.726 m^2 K/W). The Rc-value of 15-cm dry substrate layers (SC15_Dry and SP15_Dry) was about twice more than that of 15-cm wet substrate layers (SC15_Wet and SP15_Wet). The slight discrepancies of 4.3% (wet state) and 6.4% (dry state) were observed between Rc-values of 15-cm substrate layers with and without coarse recycled materials.

In the dry state, the Rc-value for 20-cm green roof specimens of NCA5-SC15_Dry, RCA5-SP15_ Dry, IMSWA5-SP15_Dry, and LECA5-SP15_Dry were obtained 1.38, 1.31, 1.26, and 1.36 m^2 K/W,

Table 4
Green roof layers' heat flow measurement results.

Specimens ID	Test duration (h)	Convergence duration (h)	Thermal conductivity (W/m·K)	Rc-value (m^2 K/W)				
				24 h before the end of data set	End of data set	The first 67% of data during the convergence period	The last 67% of data during the convergence period	Average value during the convergence period
NCA5 [22]	101	76	0.114	0.443	0.443	0.441	0.44	0.44
RCA5 [22]	101	76	0.11	0.44	0.446	0.449	0.446	0.446
IMSWA5 [12]	101	76	0.115	0.432	0.43	0.43	0.43	0.43
LECA5	101	76	0.067	0.733	0.732	0.725	0.727	0.726
SC15_Wet [22]	122	73	0.31	0.481	0.48	0.481	0.48	0.48
SC15_Dry [60]	140	116	0.15	1.038	1.04	1.036	1.043	1
SP15_Wet [22]	122	73	0.32	0.462	0.463	0.461	0.462	0.46
SP15_Dry [60]	165	75	0.16	0.94	0.93	0.93	0.94	0.94
NCA5-SC15_Wet [22]	166	118	0.27	0.743	0.75	0.748	0.746	0.75
NCA5-SC15_Dry [60]	165	120	0.142	1.42	1.4	1.4	1.4	1.38
RCA5-SP15_Wet [22]	166	118	0.28	0.713	0.72	0.715	0.724	0.72
RCA5-SP15_ Dry [60]	166	120	0.151	1.27	1.3	1.27	1.32	1.31
IMSWA5-SP15 _Wet [12]	168	120	0.27	0.732	0.735	0.728	0.726	0.735
IMSWA5-SP15 _Dry [12]	168	120	0.16	1.25	1.26	1.26	1.25	1.26
LECA5-SP15 _Wet	168	120	0.192	1.044	1.047	1.04	1.042	1.04
LECA5-SP15 _Dry	168	120	0.147	1.358	1.364	1.362	1.357	1.36

respectively. The corresponding values in the wet state for NCA5-SC15_Wet, RCA5-SP15_Wet, IMSWA5-SP15_Wet, and LECA5-SP15_Wet were 0.75, 0.72, 0.735, and 1.04 m^2 K/W, respectively. Considering the same order of the above specimens, the Rc-values of the green roof specimens in dry state was 84%, 82%, 71.4%, and 30.1% greater than those in wet state. Comparing the proposed green roof specimens with the reference green roof in a dry state, the Rc-value of 20-cm green roof specimens with drainage layers of RCA, IMSWA, and LECA (RCA5-SP15_Dry, IMSWA5-SP15_Dry, and LECA5-SP15_Dry) was respectively 0.95, 0.92, and 0.99 times that of the reference green roof (NCA5-SC15_Dry). In the wet state, the corresponding difference was 0.96, 0.98, and 1.39 times, respectively.

3.3. Water permeability

The green roof materials' water permeability values are shown in Fig. 4. According to the results, the water permeability values of granular aggregates, including NCA, IMSWA, RCA, LECA, SC, and SP, were 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, respectively. Their 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.

Table 5 presents the two-sample *t*-test method's results for the water permeability test, which were calculated using Eq. (5). For each layer, the mean of water permeability for the proposed materials was compared with that for the reference materials. As per the results, the t_{test} value of IMSWA, RCA, and LECA compared to that of NCA was obtained at 1.487, 1.536, and 6.785, respectively. The corresponding value for SP was attained at 15.855 in comparison to SC.

Considering that the results were the average of three specimens, the sum of n_1 and n_2 was 6, d_f was equal to 4 using Eq. (6). Therefore, the *t* value was extracted from the t_{test} table and obtained 2.132 with 95% confidence ($\alpha = 0.05$) and 4° of freedom (d_f). As presented in Table 5, the t_{test} results for IMSWA and RCA (1.487 and 1.536) were obtained at less than 2.132, demonstrating that the water permeability performance of the IMSWA and RCA was nearly the same as that of NCA. However, the t_{test} value between LECA and NCA was obtained at 6.785, which was more than 2.132. Therefore, there was a difference between the mean of the LECA and NCA. The t_{test} value for SP (15.855) was greater than 2.132, indicating that the mean water permeability for SC was more than that for SP.

3.4. Water retention capacity

Fig. 5 shows the water retention values of green roof materials. As per the results, the values of 9%, 18.1%, 13.77%, 18.5%, 46.73%, and 38.27% were obtained for NCA, IMSWA, RCA, LECA, SC, and SP, respectively. Their SD values were 0.71, 1.65, 0.51, 0.48, 0.68 and 0.22, respectively.

Table 5
The two-sample t_{test} method's results for the water permeability test.

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

The two-sample *t*-test method's results for the water retention capacity test are presented in Table 6. According to the coarse granular drainage materials results, the t_{test} value of IMSWA, RCA, and LECA was obtained 8.79, 9.45, and 10.2 compared to NCA. For the substrate layer, the value of 20.49 was obtained for SP in comparison to SC.

The results were the average of three specimens. Hence, the *t* value, extracted from the t_{test} table, was obtained 2.132 with 95% confidence. According to Table 6, the t_{test} results for IMSWA, RCA, and LECA (8.79, 9.45, and 9.06) were more than 2.132. So, there was a difference between the mean water retention capacity for the proposed coarse granular drainage aggregates and NCA. The t_{test} value for SP (20.49) was also obtained at more than 2.132, demonstrating that the mean water retention capacity for SP and SC cannot be considered the same.

4. Discussion

4.1. Rc-value measurement (heat resistance indicator)

The air-voids among coarse aggregates were more impacted by air-voids than coarse aggregate types, resulting in similar heat resistance of NCA5, RCA5, and IMSWA5 (0.44 m^2 K/W) [22]. However, the higher porosity of LECA than other granular aggregates led to a higher Rc-value for LECA5 (0.726 m^2 K/W). Considering the Rc-value of 15-cm dry substrate layers was twice more than that of 15-cm wet substrate layers, it can be stated that the confined air provided a higher heat resistance than the water content for the substrate layer, as mentioned by Kazemi et al. [12]. Partially replacing the organic matter with coarse recycled materials caused a narrow difference between Rc-values of 15-cm substrate layers with and without coarse recycled materials (4.3% in wet

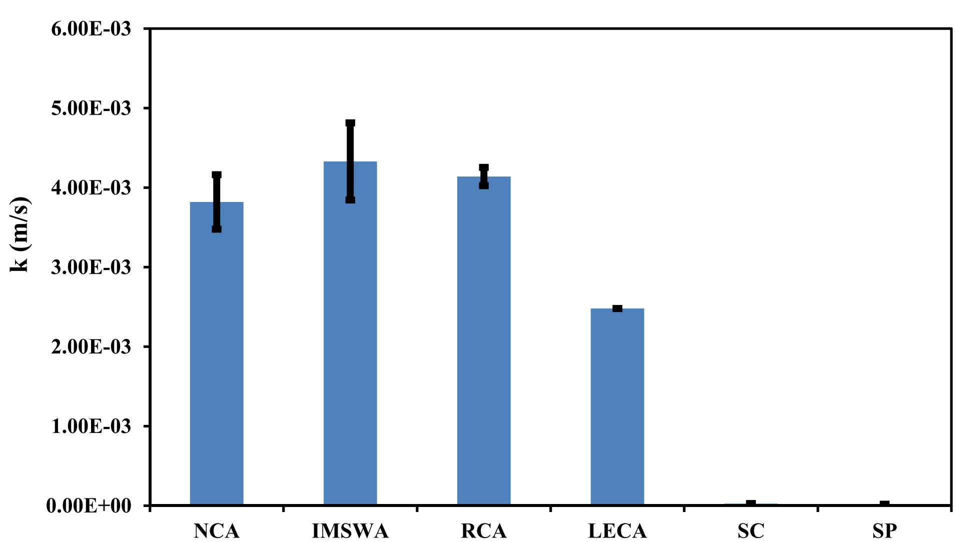

Fig. 4. Results of water permeability test.

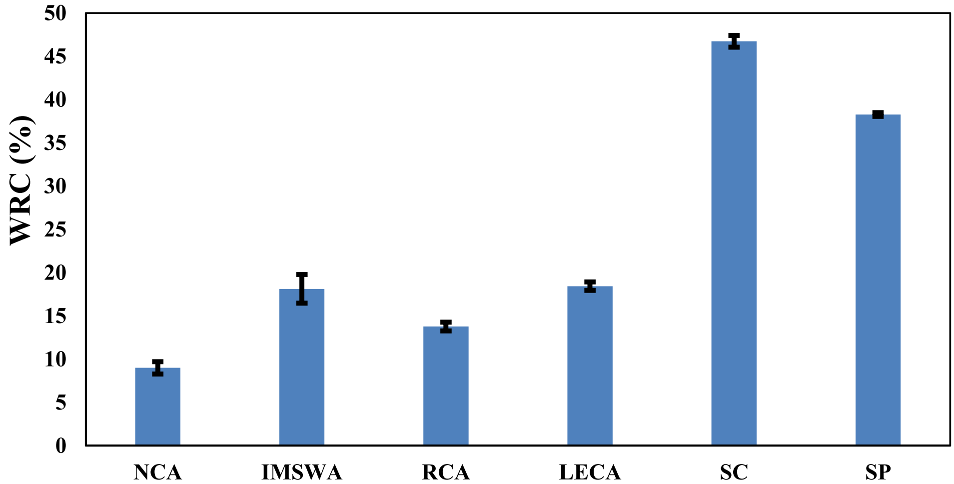

Fig. 5. Results of water retention capacity test.

Table 6
The two-sample t_{test} method's results for the water retention capacity test.

Materials ID	t_{test}
NCA	–
IMSWA	8.79
RCA	9.45
LECA	19.06
SC	–
SP	20.49

state and 6.4% in dry state). This slight difference showed that the porous coarse recycled materials' ability to withstand heat flow was somewhat lower than that of dry soil particles, even though it was negligible.

The expansion of air spaces among dry, coarse recycled materials and dry soil particles led to a better performance than the water content in soil particles to achieve a greater thermal resistance for green roof systems [4,5,12]. The highest difference between the Rc-value of dry and wet green roof systems was observed for 20-cm green roofs with a 5-cm drainage layer of NCA or RCA (NCA5-SC15_Dry, RCA5-SP15_ Dry, NCA5-SC15_Wet, and RCA5-SP15_Wet). The lowest difference (30.1%) was obtained for 20-cm green roofs with a 5-cm drainage layer of LECA (LECA5-SP15_Dry and LECA5-SP15_Wet) owing to the higher porosity of LECA than other granular aggregates. This in turn caused the drainage layer of LECA participated more in providing thermal resistance for green roof systems than the substrate layer, leading to decreasing the difference between the thermal resistance of green roofs with wet and dry substrate materials.

A comparison between the Rc-value of the proposed green roof specimens with the reference green roof in a dry state demonstrated that although there was no substantial difference between the Rc-value of proposed green roofs and the reference green roof, the LECA5-SP15_Dry specimen had the closest thermal resistance to NCA5-SC15_Dry specimen (0.99). Similar results were observed in wet state where the thermal resistance of the LECA5-SP15_Wet specimen was 1.39 more than that of NCA5-SC15_Wet specimen.

Based on the above, the lowest difference between wet and dry conditions was obtained for 20-cm green roofs with a 5-cm drainage layer of LECA (30.1%), and the highest thermal resistance was also attained for the same specimens. Since researchers have advocated for adopting lightweight roofing solutions with sufficient heat resistance for rooftops [4,78,79], the LECA5-SP15_Wet, and LECA5-SP15_Dry specimens can be considered the best configuration and materials for roofing systems due to their lowest weight and highest heat resistance.

4.2. Water permeability (water drainage indicator)

According to the t_{test} method's results, the means of water permeability for IMSWA and RCA was nearly identical to that of the coarse control aggregates (NCA). Therefore, although the type of the aggregates above differed, all of them were crushed, and their size was the same (7 mm). Therefore, the voids among aggregates controlled their water permeability performance rather than the coarse aggregates. However, the t_{test} method's result between NCA and LECA (6.785) specified a difference between the water permeability of the former and the latter. Comparing the water permeability of the NCA (3.8×10^{-3} m/s) and LECA (2.5×10^{-3} m/s) showed that the water permeability of the former was about 1.5 times more than that of the latter. The LECA was composed of rounded expanded clay aggregates, while NCA was crushed coarse materials.

Moreover, the porosity of LECA (55%) was higher than that of NCA (41.67%). In addition, LECA had the highest water absorption coefficient (0.11 kg/m^2.s$^{0.5}$) and free water content (141 kg/m^3) compared to other coarse granular aggregates, leading to increasing its water holding capacity and subsequently decreasing its water permeability value. Therefore, the rounded shape and physical properties of LECA caused its water permeability performance to be less than that of NCA.

Among coarse aggregates, the highest and lowest SD values were obtained for IMSWA (4.86×10^{-4}) and LECA (6.2×10^{-6}), respectively. It can be stated that since IMSWAs included different crushed and recycled materials, their results were more scattered than other aggregates, while the shape and type of LECAs were the same, leading to lower dispersion of data and lower SD value.

The water permeability of the green roof's substrate layer should be in the range of 10^{-5}-1.17×10^{-3} m/s, according to the recommendations given by the FLL guidelines [23]. This parameter for SC and SP was obtained 2.6×10^{-5} and 1.7×10^{-5} m/s, which were within the range given by FLL guidelines [23]. Therefore, the soil materials (SC and SP) provided an adequate water passing ability for the green roofs' substrate layer. The t_{test} results showed that the mean of water permeability for SC was more than that for SP. This value for the SC and SP was 2.6×10^{-5} and 1.7×10^{-5} m/s, respectively. The water permeability of the former was about 1.5 times more than that of the latter. Although the substrate materials' water permeability depends on their porosity and shape [2,80] and using high porous materials can lead to increasing the green roof systems' water permeability [27], there was no significant difference between the porosity of SC (48.2%) and SP (48.63%). The difference between the water permeability of SC and SP can be a consequence of coarse recycled materials in the latter, leading to generating tortuous paths for passing water through the substrate layer and subsequently decreasing the water permeability of green roof systems, similar to what was revealed by Miller [29]. Therefore, the water could easily pass through the soil's fine particles in SC. However, the partial replacement of these fine particles with coarse recycled materials in SP prevented effortlessly passing water through the substrate layer. Consequently, the ability of SC was better than that of SP.

4.3. Water retention capacity (water holding indicator)

According to the t_{test} method's results, there was a difference between the means of water retention capacity values of the proposed coarse drainage aggregates and NCA. Also, comparing the results showed that the water retention capacity value of LECA (18.5%) and IMSWA (18.1%) was obtained about 2 times more than that of NCA (9%). Moreover, the result of RCA (13.77%) was about 1.5 times more than that of NCA (9%). Therefore, higher porosity of recycled and artificial coarse aggregates (IMSWA, RCA, and LECA) than NCA led to a greater water retention capacity for the drainage layer. Moreover, the water retention capacity value of LECA and IMSWA was obtained more than that of RCA. LECA is an artificial aggregate with a high water absorption coefficient (0.11 $kg/m^2.s^{0.5}$). IMSWA included crushed brick, inert waste, crushed aggregate, crushed ceramic, and crushed glass [12], while RCA was more composed of recycled concrete coarse aggregates. Therefore, since LECA was an aggregate with high water absorption and IMSWA included different types of recycled materials such as crushed brick, inert waste, and crushed aggregate, they were proved to outperform RCA to hold more water for the drainage layer of green roof systems. It is noteworthy that due to different types of materials in IMSWA, its water retention capacity values (SD = 1.65) were more dispersed than other aggregates, while the results of LECAs were less scattered (SD = 0.48) because of their single type and regular ball-shaped form.

On the other hand, it has been suggested to choose lightweight materials for the green roof layers to apply less load to the top of structures [81]. The density of IMSWA (1147 kg/m^3) was 2.6 times more than LECA (439 kg/m^3). Therefore, LECA is recommended for the drainage layer to provide the highest water retention capacity and impose the lowest load on buildings compared to other coarse granular aggregates.

There was a difference between the mean of water retention capacity of SC and SP for the substrate materials according to the t_{test} method's results (Table 6). As shown in Fig. 5, the water retention capacity of the former (46.73%) was about 1.2 times more than the latter (38.27%). It can be stated that fine particles of soil materials in SC absorbed slightly more water than recycled coarse materials in SP. However, the results of SC and SP were within the range (35%–65%) recommended by the FLL guidelines [23], demonstrating that both SC and SP provide an adequate water retention capacity for growing plants and species, and they don't overload rooftops.

5. Conclusions

This research work assessed the water permeability, water retention capacity, and thermal resistance of green roof layers made with different recycled and artificial aggregates. The following conclusions for roofing systems can be drawn based on experimental outputs:

- The presence of air voids among dry soil particles resulted in superior thermal resistance for green roof systems than the water content in soil particles. Comparing wet and dry green roof systems' results, the highest difference was obtained between the Rc-value of 20-cm green roofs with a 5-cm drainage layer of natural coarse aggregate or recycled coarse aggregate (about 80%). The lowest difference was obtained for 20-cm green roofs with a 5-cm drainage layer of lightweight expanded clay aggregate (30.1%).
- Of all proposed green roof systems, 20-cm green roofs with a 15-cm substrate layer and 5-cm drainage layer of lightweight expanded clay aggregate had the lowest weight and the highest thermal resistance. Hence, they were introduced as the best configuration for rooftops.
- The water permeability performance of incinerated municipal solid waste aggregate and recycled coarse aggregate was nearly the same as the coarse control aggregate. Therefore, the voids among aggregates dictated their water permeability performance rather than the coarse aggregates.
- Among coarse granular aggregates used for the drainage layer, the highest porosity (55%), water absorption coefficient (0.11 $kg/m^2.s^{0.5}$), and free water content (141 kg/m^3) were obtained for lightweight expanded clay aggregate. Indeed, its physical properties and rounded shape caused the water permeability of natural coarse aggregate was obtained 1.5 times more than that of lightweight expanded clay aggregate, while the water retention capacity of the latter was obtained two times more than that of the former. Therefore, the use of lightweight expanded clay aggregate for the drainage layer provided the highest water for growing the plants and species and applied the lowest load to buildings due to its high water retention capacity and low weight, even though its water permeability was not as much as other coarse granular aggregates.
- The water permeability of the substrate without course recycled materials was about 1.5 times more than that of the substrate with course recycled materials. Considering this, the former outperformed the latter in passing the water through the substrate layer. However, the substrate either with or without course recycled materials provided the required water permeability for green roof systems.
- Although the water retention capacity of the substrate without course recycled materials was obtained slightly more than that of substrate with course recycled materials (1.2 times), the results of both were within the required range given for the water holding capacity of green roof substrate materials. Therefore, substrate with course recycled materials offered sufficient water holding capacity for growing plants, and it also didn't overload green roof systems.

Water passing and holding capacity and thermal resistance of substrate and drainage layers were measured in this study to assess the possibility of using recycled and artificial materials for green roof systems. Analysis methods have now to be employed to assess the sensitivity to physical characteristics of artificial and recycled materials used for drainage and substrate layers of green roof systems.

CRediT authorship contribution statement

Mostafa Kazemi: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luc Courard:** Writing – review & editing, Supervision. **Shady Attia:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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