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Eco-friendly green roof solutions: Investigating volcanic ash as a viable alternative to traditional substrates

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ABSTRACT

This research investigates the potential of volcanic ash as a green roof material, focusing on its thermal conductivity, physical characteristics, and permeability. Laboratory tests were conducted to determine thermal conductivity under different moisture conditions using two measurement devices, TLS 100 and HFM 436/3/1 Lambda. The results revealed that thermal conductivity increases with higher moisture content, indicating improved heat conduction as the material becomes more saturated with water. Particle size distribution analysis demonstrated that the majority of volcanic ash particles fall within the range of sand and gravel, providing a porous and well-draining material. Sand-sized particles create interconnected voids, facilitating efficient water movement, while gravel-sized particles enhance structural stability and load-bearing capacity. The limited presence of silt-sized particles further validated the material's suitability for green roof applications. Permeability tests on loosely compacted volcanic ash revealed higher permeability at 0% compaction, aligning with intended green roof configurations. This high permeability ensures effective drainage, preventing water accumulation and promoting healthy vegetation growth. At 20% compaction, the material still effectively managed water under potential compaction forces, striking a balance between drainage and water retention. Visual examination of green roof samples demonstrated that volcanic ash substrates resisted weed growth due to the absence of fertilization. While the commercial substrate exhibited better vegetation development due to added nutrients, volcanic ash substrates supported vegetation survival throughout the summer period with an irrigation system, reducing maintenance and lifecycle costs. In conclusion, the research findings indicate that volcanic ash possesses desirable thermal properties, a suitable particle size distribution, and favorable permeability characteristics for green roof applications. Its potential as a sustainable and cost-effective alternative to commercial substrates is evident, offering resilient urban landscapes with reduced environmental impact. Further exploration and optimization could solidify volcanic ash as a valuable component in advancing green roof technologies, promoting sustainable urban development.

1. Introduction

Green roofs have gained significant attention as an innovative solution for enhancing the environmental performance of buildings [1,2]. These innovative roof systems transcend the conventional by incorporating vegetation and growing media, creating a living layer that offers multifaceted advantages. They form an integral part of the "green infrastructure" concept by providing a versatile rooftop layer that emulates natural ecosystems [3]. By seamlessly integrating vegetation into the urban environment, green roofs offer an array of benefits that extend far beyond the aesthetics of traditional rooftops. Primarily, they provide stormwater management by minimizing runoff and improving water quality [4]. The inclusion of vegetation and growing media enables them to capture and retain rainwater, thus alleviating stress on stormwater infrastructure and mitigating the risk of flooding. Furthermore, green roofs act as natural heat regulators by absorbing solar radiation and releasing it as latent heat through evapotranspiration, effectively cooling the surrounding atmosphere [5,6]. This temperature moderation contributes to energy conservation and enhances thermal comfort in urban areas [7,8]. In addition to these functional attributes, green roofs foster biodiversity by offering habitats for diverse plant species, insects, birds, and other wildlife [9]. They also serve as steppingstones

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for the movement of species across fragmented urban landscapes, thereby promoting urban biodiversity conservation.

However, the traditional materials used in constructing green roofs, such as expanded clay and perlite, come with certain inherent challenges [10]. The extraction and manufacturing processes of these materials often involve substantial energy consumption and environmental repercussions. Moreover, the sourcing and availability of these conventional green roof materials can be limited, giving rise to concerns about sustainability and cost escalation [11].

Recognizing the critical need for green roof materials to exhibit specific properties and functions, such as efficient drainage and superior thermal performance, researchers and practitioners have embarked on a quest for sustainable alternatives. These alternatives aim to curtail the environmental impact of green roofs while upholding their functionality and effectiveness. Kazemi et al. [12] conducted comprehensive experiments to evaluate the water passage, retention capacity, and thermal resistance of recycled aggregates, including Recycled Coarse Aggregate (RCA) and Incinerated Municipal Solid Waste Aggregate (IMSWA), employed in the drainage layer of green roof systems. Their findings indicated the potential of these materials in reducing environmental impact compared to traditional roofing materials. However, these materials may exhibit limitations in terms of structural performance and long-term durability. Cascone and Gagliano [13] explored the feasibility of using recycled plastic granules as an alternative to natural drainage materials like perlite. Their research highlighted the similarity in properties between these recycled plastic granules and perlite, suggesting their suitability for green roof drainage layers. Nonetheless, potential drawbacks and long-term behavior of these materials in varying environmental conditions necessitate further investigation. Another study by Naranjo et al. [14] delved into the realm of recycled materials, encompassing rubber, high-density polyethylene (HDPE) trays, and polyethylene terephthalate (PET) bottles, as components of semi-intensive green roofs. These recycled materials not only trimmed costs and reduced dead loads compared to traditional drainage systems but also demonstrated the potential for environmental benefits. However, their performance over time and potential limitations, such as material degradation, necessitate judicious consideration. The comprehensive study also presented a summary table of pertinent works related to the use of recycled materials in green roofs, including recycled glass [15], recycled crushed porcelain [16], and recycled construction waste [17]. Eksi et al. [18] carried out a rigorous assessment of four recycled materials—crushed concrete, crushed bricks, sawdust, and municipal waste compost—as prospective green roof substrates. Their evaluation encompassed measurements of plant growth, along with environmental impact assessments. Although these materials exhibited promise in promoting sustainable green roofs, their specific drawbacks and limitations concerning plant support and long-term viability demand in-depth exploration. Finally, Rincón et al. [19] shed light on the benefits of integrating recycled rubber crumbs as drainage layers in green roofs. This approach champions waste reduction and the repurposing of materials. Nevertheless, it is essential to conduct a comprehensive evaluation of their environmental impact throughout their lifecycle.

While it is evident that recycled and artificial materials offer potential benefits for green roofs, it is equally essential to acknowledge their limitations, encompassing structural performance, durability, and environmental impact. These considerations assume paramount significance in the context of green roof design and construction.

This study diverges from existing research by focusing on approach: the utilization of Etna volcano ash as a constituent of green roofs. Although prior studies have examined the deployment of recycled materials and alternative substrates in green roof systems, scant scientific investigations have explored the feasibility and performance of Etna volcano ash in this context. Existing literature has predominantly concentrated on the use of volcanic ash in construction materials, such as cement and concrete, or its potential in environmental remediation applications [20–27]. The incorporation of Etna volcano ash into green roofs as a sustainable resource remains largely uncharted territory.

In this research, a series of laboratory tests to ascertain the suitability of Etna volcano ash for green roof applications were embarked on. The assessment centered on key thermo-physical attributes, including particle size, density, permeability, and thermal conductivity. Notably, thermal conductivity measurements using two distinct laboratory devices under varying moisture conditions (dry, moist, and saturated) were conducted. Encouraging preliminary results paved the way for the subsequent phase of this research. This phase involves the installation of multiple green roof samples to assess the growth potential of four different vegetation species, all while utilizing Etna volcano ash as a drainage layer and/or substrate. For comparative analysis, conventional materials like expanded clay (a traditional product) and recycled polyethylene granules (an innovative product) as drainage layers were incorporated, alongside a commercially developed growing media as the substrate. Some samples featured a combination of Etna volcano ash and varying proportions of the commercially developed growing media.

The outcomes of this study hold the promise of providing practical guidance for architects, engineers, and urban planners interested in integrating Etna volcano ash into green roof systems. Simultaneously, this research contributes to a broader scientific understanding of sustainable construction practices. By addressing the challenges linked to volcanic ash management and presenting an innovative solution for waste reduction, this research endeavors to advance the ecological transition of the built environment.

2. Materials and methods

2.1. Laboratory tests to determine thermal conductivity

2.1.1. Sample preparation

The thermal conductivity measurements on volcanic ash were conducted using the TLS 100 and HFM 436/3/1 Lambda devices, with three and two different samples, respectively. These samples were intentionally varied in terms of moisture content, including dry, moist, and saturated conditions, to align with the Guidelines for the planning, construction, and maintenance of green roofs published by Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (FLL) [28] for laboratory material testing.

In this study, the aim was to focus on analyzing the thermal properties of volcanic ash sourced from the Etna volcano, Italy. This volcanic ash is of particular interest due to its relevance to green roof applications.

2.1.1.1. Drying. The drying process aimed to eliminate moisture from the volcanic ash sample. This step followed the guidelines provided in Attachment B.1.3 of the FLL. Initially, the volcanic ash was placed within a container (Fig. 1, on the left), and its initial weight was precisely measured using a high-precision balance. Subsequently, the sample was carefully placed inside an oven preheated to 105 °C (Fig. 1, in the middle). Once the oven reached the desired temperature, weight measurements were taken at intervals until a constant weight was achieved, indicating that the sample was completely dried.

2.1.1.2. Moistening. The objective of moistening was to bring the sample to a specific moisture level. This process followed the instructions outlined in Attachment B.1.3 of the FLL. A predetermined quantity of water was added to the dry sample, increasing its weight by approximately 10%. The sample was then placed within a 20 cm high container (Fig. 1, on the right). To prevent material leakage, a geotextile layer was positioned at the container's bottom before adding the dry volcanic ash, filling it up to a height of 15 cm. The material was compacted to minimize voids, and its weight was measured using a high-precision balance. Around 300 ml of water was added to the sample, resulting in a moist state, represented by a 10% weight increase. Following this, the sample

Fig. 1. Ash volcanic sample preparation to achieve the moist state.

was allowed to drain through circular holes at the container's base for approximately one hour and thirty minutes before measuring its weight, resulting in a weight of 3.32 kg.

The instructions provided in Attachment B.1 of the FLL were followed when creating holes at the bottom of the cylindrical tube used during the saturation phase, which featured a total of 125 holes necessary for proper excess water drainage (Fig. 2, on the left).

2.1.1.3. Saturation. The saturation phase aimed to achieve complete saturation of the volcanic ash sample. This phase followed the instructions specified in Attachment B.2 of the FLL. To prevent material leakage through the base holes, a fine-mesh and geotextile were positioned at the bottom of the cylindrical tube. The volcanic ash was then added to the tube, compacted to reduce voids, and filled to a height of 18 cm. A geotextile and mesh were placed on top of the material to prevent floating, and a lead disc was added on top of them (Fig. 2, in the middle). The sample was positioned inside a tank, with two metal bars at the base lifting the sample one centimeter above the bottom of the container. This arrangement facilitated capillary saturation from the bottom to the top of the sample (Fig. 2, on the right). The saturation process comprised four phases:

1. Gradual filling of the tank with water until the cylindrical tube's height reached 17 cm (1 cm below the material's height in the sample, following point B.2.3 of the FLL).
2. Allowing water to rise to the surface of the sample through capillary action, followed by adding an additional centimeter of water above the material's height in the cylindrical tube.
3. Leaving the sample in this saturated condition for approximately 24 h to ensure thorough saturation.
4. Removing the cylindrical tube from the tank, allowing excess water to drain for approximately 2 h before proceeding with weight and thermal conductivity measurements.

These distinct steps in the sample preparation process were carefully selected to achieve specific moisture conditions and ensure alignment with the research objectives, allowing accurate thermal conductivity measurements under varying moisture levels.

2.1.2. *Test execution*

Once the samples were prepared in the dry, moist, and saturated states, thermal conductivity measurements (W/mK) were performed using the TLS 100 (Fig. 3) and HFM 436/3/1 Lambda (Fig. 4) devices. Calibration measurements were conducted prior to the TLS 100 measurements using a provided sample in the Thermtest Portable device to ensure the accuracy and reliability of the measurements. Similarly, the benchtop thermal conductivity sensor, HFM 436/3/1 Lambda, was tested by initiating the first measurement on Neopor (insulating material). These calibration measurements are essential to establish a baseline for accurate thermal conductivity measurements.

For TLS 100 measurements, three different points on each sample in the dry, moist, and saturated states were selected, avoiding the edges of the container to minimize measurement errors caused by edge effects. At each selected point, three measurements were taken at approximately 15-minute intervals to account for any potential variations in the material's thermal conductivity over time. The standard deviations of these measurements were calculated to assess the degree of variation. Calibration measurements were also conducted to ensure that any variations or errors introduced by the measuring devices were accounted for and corrected.

Before each measurement with the HFM 436/3/1 Lambda, the weight was measured to determine the sample density, and the sample data was entered into the Q-Lab software installed on the computer. The specific data points recorded for each sample included the density of the volcanic ash (ρ), the height of the square container (h), the average temperature (Mean T), and the temperature difference between the two

Fig. 3. TLS 100 measurements.

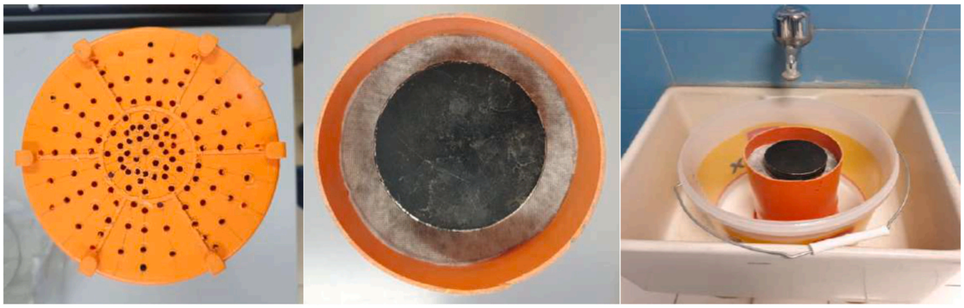

Fig. 2. Tube base with 125 holes (on the left), geotextile mesh, mesh, and lead disc on the top of the material to avoid floating (in the middle), capillary saturation of the sample (on the right).

Fig. 4. HFM 436/3/1 Lambda measurements.

plates (ΔT) (Table 1). These data points were essential inputs for the Q-Lab software to calculate the thermal conductivity of the volcanic ash material.

In selecting the temperature range for thermal conductivity measurements using the HFM 436/3/1 Lambda device, the goal was to encompass a range of temperatures that are relevant to the study while ensuring accurate results (Table 1). The range of 10–30 °C was chosen as it represents typical environmental conditions that the volcanic ash material may experience in real-world applications, such as green roofs. This range is relevant to the study's objectives as it covers the expected temperature variations in the field. Additionally, this temperature range is commonly used in thermal conductivity measurements for materials with similar applications. By choosing this range, the aim was to obtain data that would be directly applicable to practical scenarios where the volcanic ash material might be used.

2.2. *Laboratory tests to determine physical characteristics*

Representative samples of volcanic ash were collected from the desired locations, ensuring that they accurately represented the volcanic ash deposits under investigation. Special care was taken during the sampling process to avoid contamination and preserve the natural characteristics of the volcanic ash.

The collected volcanic ash samples were transported to the laboratory of the University of Catania in sealed containers to maintain their original moisture content and prevent moisture loss or gain. Upon arrival, the samples were air-dried at room temperature, ensuring the removal of excess moisture while preserving the natural state of the volcanic ash.

Each test method described in the following was replicated twice to ensure the robustness and reliability of the results.

2.2.1. *Particle size distribution*

The particle size distribution of volcanic ash samples was determined using the Standard Test Method for Particle-Size Analysis of Soils [29], with necessary adaptations for volcanic ash analysis. The samples were gently disaggregated to ensure homogeneity throughout the material. This step aimed to break down any agglomerated particles and ensure representative sub-sampling.

A precise amount of 100 g from each prepared sample was weighed using an analytical balance and subsequently placed onto a nest of sieves. The sieves used in the analysis consisted of a series of mesh sizes, ranging from coarse to fine, with the following openings: 9.50, 4.75, 2.00, 0.850, 0.425, 0.250, 0.150, 0.075, 0.063, 0.053, and 0.038 mm (Fig. 5, on the left, and Table 2). Due to the small particle dimension of the volcanic ash, some sieves smaller than 0.075 mm were used, necessitating an adaptation to the Standard Test Method for Particle-Size Analysis of Soils [29]. The sieves were carefully arranged in descending order, with the coarsest sieve at the top and the finest at the bottom.

Table 1
Set of temperatures for measuring thermal conductivity using the HFM 436/3/1 Lambda.

Average T [°C]	Measurement range [°C]	T Upper [°C]	T Lower [°C]
20.0	20.0	30.0	10.0
22.50	20.0	32.5	12.5
25.0	20.0	35.0	15.0
27.50	20.0	37.5	17.5
30.0	20.0	40.0	20.0

For the mechanical shaking process, a mechanical sieve shaker was employed with settings conforming to ASTM guidelines for soil particle size analysis. The volcanic ash samples in the sieves were subjected to mechanical shaking for a duration of 10 min, ensuring efficient and consistent agitation.

The mechanical shaking process facilitated the sieving of the volcanic ash samples and the retention of particles on the sieves according to their respective sizes. Following the shaking process, the retained material on each sieve was carefully collected, and its mass was determined using a calibrated analytical balance. The mass retained on each sieve was recorded, and the percentage of material retained was calculated by dividing the mass retained by the initial sample mass.

The obtained data on the percentage of material retained on each sieve was then utilized to construct a particle size distribution curve. This curve represents the variation in particle size distribution across different sieve sizes or openings. By plotting the percentage retained on the y-axis against the corresponding sieve size on the x-axis, the particle size distribution curve provides valuable insights into the size distribution characteristics of the volcanic ash samples.

2.2.2. *Maximum and minimum index density*

The standard test methods for Maximum and Minimum Index Density and Unit Weight of Soils [30,31] were adapted and applied to determine the maximum and minimum index density, as well as the unit weight of volcanic ash samples. These test methods were employed to gain insights into the compaction characteristics and density variations of volcanic ash, which are essential for understanding its engineering behavior.

To prepare the volcanic ash samples for testing, a predetermined quantity of the air-dried ash was accurately weighed. The selected amount of volcanic ash was then placed into a compaction mold, such as a Proctor mold, with attention given to proper alignment and compaction conditions (Fig. 5, in the middle).

Compaction of the volcanic ash samples was carried out using a compaction device suitable for the specific test method and the compaction energy varying between 3% and 10% of the maximum energy that is possible to be applied. The compaction process involved applying a specified number of compactions blows, with each layer receiving uniform compaction energy. Consistency in the compaction process was maintained across all samples to ensure reliable and comparable results.

After compaction, the compacted volcanic ash specimens were carefully removed from the mold, and any excess ash was trimmed using appropriate tools. The specimens were then weighed accurately to determine their mass.

The volume of the compacted volcanic ash specimens was determined using displacement methods, such as the water displacement method. This volume measurement facilitated the calculation of the maximum and minimum index densities and the unit weight of the volcanic ash.

Using the mass and volume measurements, the maximum and minimum index densities, as well as the unit weight, were computed. These values provided important information about the compaction characteristics, density variations, and engineering behavior of the volcanic ash.

2.2.3. *Permeability characteristics*

The standard test method for Permeability of Granular Soils

Fig. 5. Sieves for particle size analysis (on the left), maximum density equipment (in the middle), permeability test (on the right).

Table 2
Sieve numbers and corresponding openings.

Sieve Number	Opening (mm)
4	4.75
10	2.00
20	0.850
40	0.425
60	0.250
100	0.150
200	0.075
250	0.063
270	0.053
400	0.038

(Constant Head) [32] was applied to determine the permeability characteristics of volcanic ash samples. This test method provides valuable insights into the flow of water through granular soils, including volcanic ash, which is crucial for understanding its hydraulic behavior. The permeability was determined with 0% compaction and 20% compaction.

To conduct the permeability test, a permeameter apparatus suitable for constant head permeability tests was employed (Fig. 5, on the right). The permeameter apparatus consisted of a permeability cell with fixed dimensions and a constant water head setup.

The volcanic ash samples used in this test were carefully prepared by breaking down any large aggregates or clumps and ensuring homogeneity throughout the material. A precise amount of 500 g of volcanic ash was used for each test, and this amount was chosen to represent typical sample sizes used in similar studies and to ensure the reliability of the results.

A constant water head was established by maintaining a steady flow of water through the permeability cell. To ensure a uniform and constant head throughout the test, a specifically designed flow control system within the apparatus was employed. This system allowed for precise regulation of the flow rate, which was continuously monitored and adjusted as needed. The goal was to maintain a consistent head of water over the specimen to create ideal test conditions.

The water flow through the specimen was allowed to stabilize, ensuring that a steady-state condition was reached before data collection commenced.

The volume of water flowing through the volcanic ash specimen per unit time was measured (Fig. 6). This data was used to calculate the hydraulic conductivity or permeability of the volcanic ash using Darcy's law, as follows:

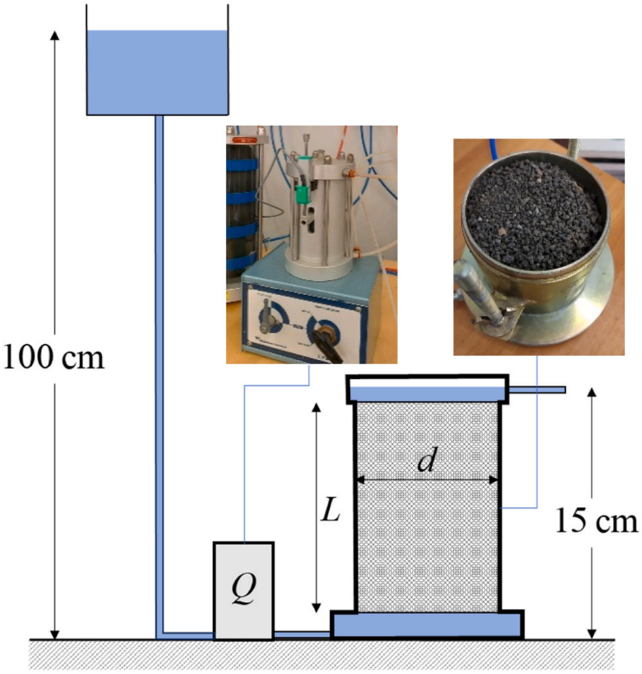

Fig. 6. Schematic representation of the permeability test.

$$k = \frac{Q}{A \times i} \tag{1}$$

where k is the coefficient of permeability, Q is the water flow (195 cm^3/s without any compaction and 155 cm^3/s with 20% of compaction), A is the sample's cross section (81.03 cm^2) and i is the hydraulic gradient that is determined as follows:

$$i = \frac{h_m - h_v}{L} \tag{2}$$

where h_m is the upstream load (100 cm), h_v is the downstream load (15 cm) and L is the sample's height (11.67 cm).

3. Results

3.1. Thermal conductivity

Table 3 presents the thermal conductivity values of volcanic ash in different moisture conditions using the TLS 100 device. The table includes three moisture conditions: dry, moist, and saturated, along with their respective thermal conductivity values.

As expected, the thermal conductivity of volcanic ash increases with increasing moisture content. The dry condition has the lowest thermal conductivity of 0.125 W/mK, while the saturated condition has the highest thermal conductivity of 0.278 W/mK.

It is noteworthy that the thermal conductivity measured under moist conditions closely approximates the thermal conductivity observed in saturated conditions, with a value of approximately 0.035 W/mK. This result can be justified by the fact that although the FLL standard specifies a weight increase of only 10% for the moist condition, volcanic ash, being a highly permeable and hygroscopic material, does not absorb water significantly. Therefore, a 10% weight increase can be considered very similar to the maximum weight the material reaches in the saturated condition. This consideration is further supported by the observations of the densities evaluated under different moisture conditions, as will be discussed in the following.

Fig. 7 provides the thermal conductivity values of volcanic ash under different moisture conditions (i.e., dry, moist, and saturated) and mean temperatures (10, 20, and 30 °C) determined by the HFM 346/3/1 Lambda device. In the same figure, the values determined through the TLS equipment are also shown.

It can be noticed that the thermal conductivity increases with the increase of the water content, as previously observed (TLS measurement). It also confirms that the thermal conductivity has a very low variation between moist and saturated conditions, just 0.02 W/mK for this set of experiments.

For a defined water content (i.e., dry, moist, or saturated), the increase in temperature, from 10° to 30°C, has a negligible effect on the thermal conductivity of less than 0.1%. A minimal variation of about 0.007 W/mK at 30 °C was observed for the moist condition.

These findings have important implications for practical applications, especially in the context of green roof systems and construction practices. The thermal conductivity values of volcanic ash under different moisture conditions provide critical insights into its suitability as a construction material for green roofs. The low thermal conductivity in the dry condition suggests that volcanic ash can serve as an effective insulating material when used in construction. The similarity in thermal conductivity between moist and saturated conditions indicates that the material's thermal performance remains relatively consistent under varying moisture levels, making it a reliable choice for green roof applications.

Furthermore, the minimal influence of temperature variations on thermal conductivity suggests that volcanic ash can maintain its insulating properties across a range of environmental conditions. This stability is valuable for ensuring consistent thermal performance in green roofs, which are exposed to fluctuating temperatures throughout the year.

Table 3
Thermal conductivity of volcanic ash in different moisture conditions using TLS 100.

Moisture level	Thermal conductivity [W/mK]	Standard deviation [W/mK]
Dry (0% Moisture)	0.125	0.0014
Low Moisture (20% Moisture)	0.243	0.0025
Saturated (100% Moisture)	0.278	0.0208

Note: The values presented in the table represent the average thermal conductivity measured at three different points for each moisture condition.

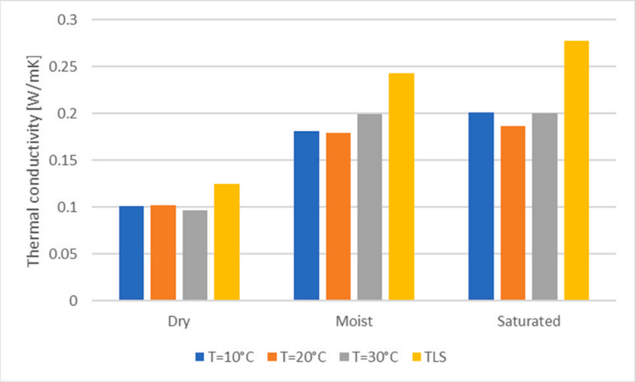

Fig. 7. Thermal conductivity of volcanic ash in different moisture conditions and mean temperatures.

The thermal conductivity results demonstrate that volcanic ash possesses favorable thermal properties for green roof systems and construction. Its low thermal conductivity, resistance to moisture-induced changes, and temperature stability make it a promising material for enhancing the energy efficiency of buildings.

For a defined water content (i.e., dry, moist, or saturated), the increase in temperature, from 10° to 30°C, has a negligible effect on the thermal conductivity of less than 0.1%. This minimal variation can be attributed to the inherent thermal properties of volcanic ash, which make it relatively insensitive to temperature changes in terms of its thermal conductivity.

Volcanic ash, as a natural material, possesses properties that contribute to its stable thermal performance across a range of temperatures. These properties include its low thermal mass and high porosity, which limit the impact of temperature fluctuations on its ability to conduct heat. Additionally, volcanic ash's composition and structure provide inherent insulation, reducing its susceptibility to temperature-induced changes in thermal conductivity.

In summary, the observed minimal influence of temperature variations on the thermal conductivity of volcanic ash can be attributed to its unique properties, including low thermal mass, high porosity, and inherent insulation characteristics. These attributes make volcanic ash an excellent choice for maintaining consistent thermal performance in green roof systems exposed to varying environmental temperatures throughout the year.

It can be noticed that the thermal conductivity increases with the increase of the water content, as previously observed (TLS measurement). It also confirms that the thermal conductivity has a very low variation between moist and saturated conditions, just 0.02 W/mK for this set of experiments.

However, it's essential to acknowledge and discuss the differences observed in thermal conductivity measurements between the two devices used in this study, the HFM Lambda and TLS 100. These variations can be attributed to the distinct measurement methods employed by each device. These inherent measurement method differences can result in variations in thermal conductivity values, as previously noted [13].

While such differences in measurement values exist, it's crucial to consider their implications for the study's conclusions. The variations observed between the two devices underline the importance of selecting an appropriate measurement method that aligns with the specific requirements of a given application. In the context of green roof systems and construction practices, where accurate thermal conductivity values are essential for material selection and performance evaluation, researchers and practitioners should carefully choose the measurement device that best suits their needs.

The observed differences in thermal conductivity measurements between the HFM Lambda and TLS 100 devices emphasize the significance of measurement methodology selection for specific applications. Researchers and practitioners in the field of construction and green roof systems should consider these variations when interpreting thermal conductivity data for material selection and performance assessment.

Density of a substrate is a fundamental property in a green roof system, as it determines the extra weight added to a building roof and must be carefully evaluated, especially considering its interaction with changes in moisture content [33].

Table 4 presents the density values for volcanic ash under different moisture conditions: dry, low moisture (20% moisture), and saturated (100% moisture).

Specifically, the minimum density measured in the dry condition was 1043 kg/m^3 , while the maximum density measured in the saturated condition was 1334 kg/m^3 , suggesting that the material has reached its maximum water-holding capacity. This result confirms that volcanic ash, being a highly permeable and hygroscopic material, does not significantly absorb water.

It is evident that densities corresponding to 20% and 100% moisture content are relatively similar, whereas the density of the dry sample is different. This observation highlights the interplay between moisture content and density in influencing the thermal conductivity of volcanic ash.

It is important to emphasize that both moisture content and density are critical factors to consider when evaluating the thermal conductivity of volcanic ash. Moisture content affects thermal conductivity by altering the heat transfer properties of the material, while density also plays a significant role in determining the overall thermal behavior.

3.2. *Particle size distribution*

The particle size distribution analysis is a crucial aspect of characterizing the physical properties of volcanic ash as a potential green roof material. Fig. 8 visually represents the particle size distribution, confirming the dominance of sand and gravel-sized particles while showing the minor contribution of silt-sized particles.

Particle size distribution refers to the range of particle sizes present in a material and plays a vital role in determining its behavior and suitability for specific applications.

The results indicate that the majority of the material's particles fall within the range of sand and gravel, with approximately 68% having a diameter between 0.063 and 2.00 mm, which corresponds to the typical size range of sand particles. Additionally, about 30% of the material's particles have a diameter larger than 2 mm, classifying them as gravel-sized particles. In practical terms, this particle size distribution has significant implications for the behavior of volcanic ash when used in green roof applications.

The predominance of sand-sized particles within the material is highly significant for green roofs. Porosity and permeability are critical characteristics in green roof systems. Porosity refers to the amount of open space within a material, while permeability relates to its ability to allow the passage of fluids, such as water. These properties are essential in green roofs for several reasons.

Firstly, porosity ensures that the green roof substrate can retain moisture and support vegetation while preventing waterlogging. It allows excess water to drain efficiently, preventing water accumulation that could harm both the vegetation and the structural integrity of the green roof.

Table 4

Density of volcanic ash in different moisture conditions.

Moisture level	Density [kg/m^3]
Dry (0% Moisture)	1043
Low Moisture (20% Moisture)	1326
Saturated (100% Moisture)	1334

Secondly, permeability plays a crucial role in managing stormwater. It allows rainwater to pass through the substrate, reducing the risk of runoff and helping to mitigate urban heat island effects. It also assists in maintaining a stable and healthy ecosystem on the green roof.

The presence of sand-sized particles within volcanic ash enhances its porosity and permeability. Sand particles create spaces between them, facilitating water movement through the material. This characteristic aligns perfectly with the requirements of green roof systems, as it ensures efficient drainage of excess water and maintains a healthy environment for vegetation.

Furthermore, the inclusion of gravel-sized particles within the material enhances its structural stability and load-bearing capacity. Gravel particles provide interlocking and compactness, which can help the green roof substrate withstand the forces exerted on it, such as wind and foot traffic, without significant deformation or displacement.

The particle size distribution of volcanic ash is highly advantageous for green roof systems. It combines the benefits of efficient water drainage due to sand-sized particles and structural stability from gravel-sized particles, making it a well-suited material for sustainable and resilient green roofs.

In green roofs, structural stability is vital to ensure that the substrate can withstand various external forces and environmental conditions. These forces may include wind loads, especially in taller buildings, as well as the weight of foot traffic during maintenance and inspections. Without sufficient structural stability, the green roof substrate could deform or shift, potentially compromising the integrity of the entire system. The interlocking and compact nature of gravel-sized particles in volcanic ash helps prevent significant deformation or displacement, maintaining the structural integrity of the green roof over time.

Load-bearing capacity is equally important for green roofs, as it determines the maximum weight that the substrate can support. The ability to bear loads is particularly relevant in situations where additional equipment or installations are placed on the green roof, such as solar panels or rooftop gardens. Gravel-sized particles contribute to load-bearing capacity by providing a stable and solid foundation, reducing the risk of subsidence or damage due to excessive weight.

In summary, the inclusion of gravel-sized particles in volcanic ash is instrumental in ensuring the long-term performance and durability of green roof systems. These particles enhance structural stability, preventing deformation and maintaining the substrate's integrity, while also increasing load-bearing capacity, allowing for the support of various elements on the green roof. These characteristics are essential for the sustainable and resilient operation of green roofs throughout their lifecycle.

The presence of silt-sized particles, constituting approximately 2% of the material, is indeed a notable aspect of the particle size distribution in volcanic ash. In the context of green roof applications, this proportion can be considered relatively low and, for several reasons, is unlikely to have significant implications for performance.

Silt-sized particles, with diameters less than 0.063 mm, are finer in texture compared to sand and gravel-sized particles. While they can influence certain material properties, their limited representation suggests that their impact on green roof performance is generally negligible.

One aspect to consider is that silt-sized particles could potentially affect the retention of fine sediments or nutrients, which might be beneficial for specific vegetation types on green roofs. However, their low proportion implies that this effect is likely to be minimal and can be addressed through appropriate planting and maintenance practices.

Overall, the relatively low presence of silt-sized particles in volcanic ash, at around 2%, is not expected to significantly impact the behavior or suitability of the material for green roof applications. The dominant sand and gravel-sized particles primarily contribute to the desired properties of porosity, permeability, and structural stability, making volcanic ash well-suited for sustainable and resilient green roofs.

The particle size distribution of volcanic ash offers a strong foundation for its suitability as a green roof material, aligning effectively

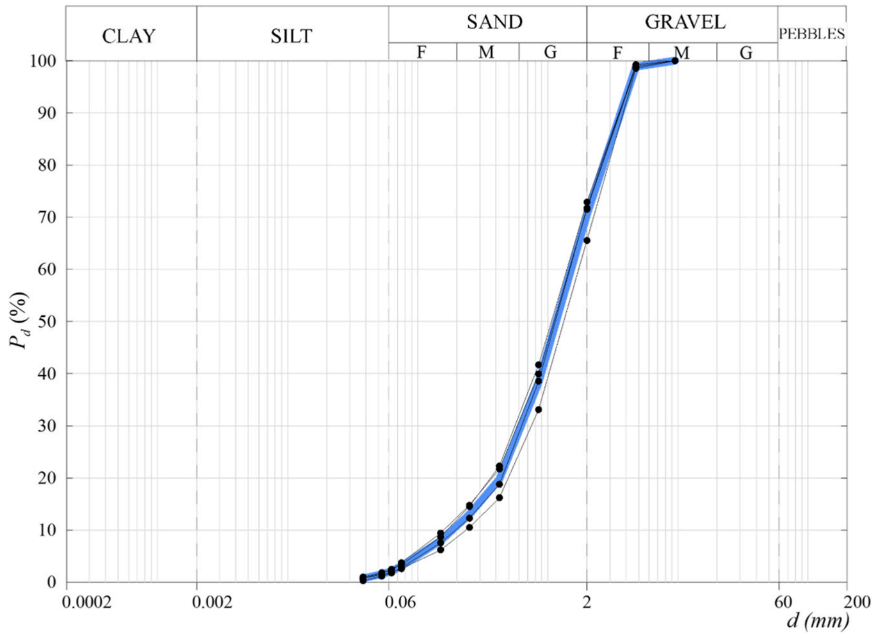

Fig. 8. Particle size distribution of volcanic ash.

with the specific requirements and standards established for green roof systems.

One of the key standards that the particle size distribution of volcanic ash aligns with is efficient water management, which is fundamental in green roof design. For instance, the predominance of sand-sized particles, accounting for about 68% of the material, enhances porosity and permeability. This is in line with green roof standards that emphasize the need for substrates to efficiently retain moisture to support vegetation while preventing waterlogging, ultimately ensuring the well-being of the green roof ecosystem. Moreover, the efficient permeability provided by the sand-sized particles aids in managing stormwater, reducing runoff, and contributing to the mitigation of urban heat island effects, which are critical environmental considerations for green roofs.

Additionally, the presence of approximately 30% gravel-sized particles in volcanic ash offers structural stability and load-bearing capacity. This feature is essential for meeting the standards related to the long-term performance and durability of green roof systems, especially in situations where external forces such as wind loads or additional installations like solar panels are involved. The interlocking and compact nature of these gravel-sized particles supports the substrate's ability to withstand these forces, ensuring the green roof's structural integrity over time.

In summary, the particle size distribution of volcanic ash harmonizes with established green roof requirements and standards, making it a well-suited material for sustainable and resilient green roofs. Its capacity for efficient water drainage, structural stability, and load-bearing align with the specific demands of green roof systems, contributing to their overall success and environmental benefits.

3.3. Index density of volcanic ash

The density of volcanic ash at varying levels of compaction is a critical property to assess its suitability for green roof applications. The research conducted, as depicted in Fig. 9, provides valuable insights into the relationship between compaction power and the resulting minimum and maximum densities of the material.

In this study, "compaction power (%)" refers to the relative measure of the energy applied to compact the volcanic ash material, expressed as a percentage. This term is intended to represent the intensity or degree of the compaction effort applied to the material, relative to a standard or baseline compaction energy level typically employed in civil engineering practices, such as that used in standard Proctor tests.

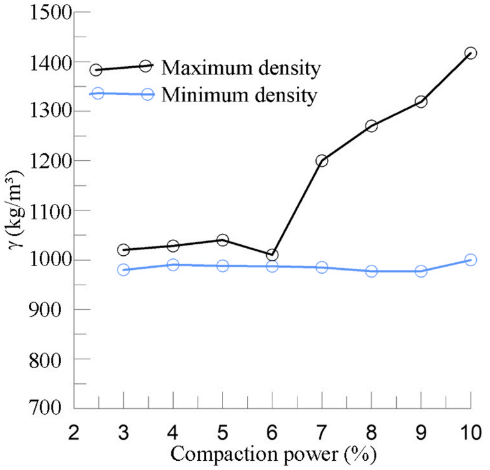

Fig. 9. Relationship between compaction power and maximum/minimum density of volcanic ash.

Fig. 9 illustrates the relationship between compaction power (X-axis) and the corresponding maximum (black line) and minimum (blue line) densities of volcanic ash. The term "compaction power (%)" along the X-axis is used to quantify and compare the varying degrees of compaction energy applied to the volcanic ash samples. This measure facilitates an understanding of how different levels of compaction influence the material's physical properties, which is crucial for assessing its suitability for green roof applications.

Starting with the minimum density, which represents the loosely compacted state of the material, the average value recorded is 986 kg/ m^3 . This value is essential as it signifies the density of the volcanic ash when it is loosely placed on a green roof without any significant compaction force applied.

In the context of green roof applications, the significance of this property becomes evident. A low minimum density is desirable for green roof materials for several reasons:

- Lightweight Nature: The low minimum density contributes to the lightweight nature of the substrate. When volcanic ash is loosely placed on a green roof, it adds minimal weight to the overall structure. This is particularly important for green roofs, as they are often added to existing buildings, and excessive weight could pose structural challenges. Additionally, the lightweight substrate makes installation and maintenance easier and safer.
- Reduced Load on Roof Structure: Green roofs with low-density substrates place less load on the roof structure beneath them. This is critical for both new and retrofit green roof projects, as it ensures that the existing building can support the additional weight without the need for costly structural modifications.
- Enhanced Plant Growth: The low-density substrate provides an optimal environment for plant growth. It allows plant roots to penetrate and expand easily, promoting healthy vegetation on the green roof.

In summary, the minimum density of volcanic ash in its loosely compacted state is a crucial property for green roof applications due to its contribution to lightweight substrates, reduced structural load, and support for healthy plant growth on green roofs.

In contrast, the maximum density of the volcanic ash varies depending on the applied compaction power. As the compaction power increases, the maximum density also rises. This variation in maximum density is significant for the practical use of volcanic ash in green roofs and has implications for factors like load-bearing capacity and water retention.

The relationship between compaction power and maximum density is not linear, primarily due to the changing packing arrangement of particles. As compaction force increases, particles in the volcanic ash pack more closely together, reducing the void spaces between them. However, beyond a certain point, further compaction may lead to particles rearranging in a way that does not result in a proportional increase in density.

The practical implications of this phenomenon include:

- Load-Bearing Capacity: The maximum density achieved with higher compaction forces results in denser packing of particles. This increased density enhances the load-bearing capacity of the green roof substrate. In situations where green roofs may need to support additional equipment, like solar panels or rooftop gardens, the ability of the substrate to withstand these loads is crucial. Therefore, the compaction process can be tailored to achieve the desired load-bearing capacity based on project-specific requirements.
- Water Retention: The density of the substrate also affects its water retention characteristics. Loosely compacted volcanic ash with lower density may retain water more effectively due to its greater pore space. This can be advantageous for green roofs in arid or semi-arid climates where water conservation is a priority. Conversely, denser substrates may have reduced water retention but can be beneficial in areas with high rainfall to prevent waterlogging.

In summary, the maximum density of volcanic ash varies with compaction power, allowing for the adjustment of load-bearing capacity and water retention based on specific project needs. This flexibility in density control adds versatility to the use of volcanic ash in green roof applications, allowing it to be tailored to local climate conditions and structural requirements, with compaction power measured serving as a key parameter.

3.4. *Permeability test*

The permeability tests conducted on loosely compacted volcanic ash material offer valuable insights into its hydraulic behavior and its relevance to green roof applications. It is important to clarify the meaning of the two compaction levels and how they were achieved.

The maximum density of the volcanic ash material is naturally close to the minimum density, reflecting its inherent characteristics unless significant compaction energy is applied. This inherent quality implies that the material possesses numerous natural voids and open spaces between particles, which can significantly influence its permeability.

To assess the permeability characteristics of the material under conditions relevant to green roofs, two specific compaction percentages were selected: 0% and 20%. These percentages represent different levels of compaction and simulate scenarios encountered during the life cycle of a green roof.

At 0% compaction, the material was tested in its loosely arranged state, replicating its condition when initially placed on a green roof. This condition closely mimics the naturally occurring state of volcanic ash on a green roof.

In contrast, the 20% compaction level represents the effect of higher compaction energy, which can result from factors like rainfall or human activity on the green roof. This level of compaction reflects a more compressed state of the material.

During testing, the permeability at 0% compaction was measured at 0.0033 m/s. This value signifies the rate at which water can flow through the material when it maintains a loose structure. The higher permeability observed at 0% compaction is expected, as the loose arrangement allows water to pass more freely through the voids and gaps between particles.

It is important to note that as moisture content increases, there is a corresponding increase in density, which is typical for hygroscopic materials like volcanic ash. This increase in density can affect permeability to some extent. In this study, the 20% moisture content scenario led to an increase in density compared to the dry state. However, even with this increase in density, the material still exhibited acceptable permeability for green roof applications, as evidenced by a permeability value of 0.0026 m/s at the 20% compaction level.

The permeability values obtained at both 0% and 20% compaction levels hold particular significance for green roof applications. Given that green roofs typically employ lightweight and porous materials, the 0% compaction state aligns closely with the intended configuration of volcanic ash on a green roof. Therefore, the higher permeability value at 0% compaction indicates that the material can efficiently drain excess water, preventing waterlogging and promoting healthy vegetation growth.

Moreover, the 20% compaction level provides insight into the material's behavior under potential compaction forces experienced during the lifespan of a green roof. While the permeability decreases at this level compared to the 0% compaction scenario, it remains within an acceptable range for green roof applications. This suggests that under conditions of heavy rainfall or significant foot traffic, the material can effectively retain and manage water to some extent, providing a balanced approach between drainage and water retention.

4. Discussion

To assess the validity of the obtained results, it is essential to compare them with previous research that applied similar methodologies to determine properties, both for the drainage layer and the substrate.

Following the previous analyses, it is possible to consider the utilization of volcanic ash as a drainage material itself. A comparison with the physical properties of drainage materials is also presented. In a previous study (Cascone and Gagliano, 2022) [13], the particle size distribution, minimum and maximum density, and permeability of recycled polyethylene granules (MAT.1, MAT.2, MAT.3, MAT.4, and MAT.6) and perlite (MAT.5) used as materials for the drainage layer of green roofs were determined.

4.1. Particle size distribution and density

Regarding the particle size distribution, perlite predominantly consists of fine particles under 2 mm in diameter (98.35%), compared to the 70% of volcanic ash. In contrast, the plastic materials exhibit larger particle sizes, with MAT.3 being the most varied, with particles ranging between 4.75 mm and 3.35 mm in diameter. MAT.1 showcases larger particle sizes than other plastic materials, with 54.95% having a diameter exceeding 8 mm.

Table 5 compares the bulk density values of different materials used for the drainage layer in green roof systems (expanded clay, perlite, polyethylene), as well as volcanic ash under two moisture conditions: dry and saturated.

Expanded clay and perlite exhibit low bulk density values, making them suitable choices for lightweight and efficient drainage layers. However, their bulk density increases with moisture content, which might impact their performance in saturated conditions.

Polyethylene stands out as a material with consistent bulk density across moisture conditions, potentially offering stable drainage capabilities in various scenarios.

Volcanic ash has notably higher bulk density values compared to the other materials, about 2.5 times higher than perlite and expanded clay under saturated conditions, which might make it less favorable for lightweight green roof systems. Its bulk density also increases with moisture content, indicating potential challenges in drainage and load-bearing capacity, particularly in saturated conditions.

Designers and practitioners can use this table to make informed decisions while selecting appropriate materials for green roof drainage layers based on their desired bulk density and performance characteristics under different moisture conditions.

4.2. Thermal conductivity

In a previous study (Cascone and Gagliano, 2023) [34] the thermal conductivity of three different commercial substrates for green roofs (S1, S2, and S3) under dry, wet, and saturated conditions was determined. Each substrate was designed with specific characteristics and components to meet different requirements, such as nutrient availability, water retention, and local material availability.

Table 6 compares the thermal conductivity of the three commercial substrates and volcanic ash under three moisture conditions: dry, moist, and saturated.

The variations in thermal conductivity among materials, including the commercial substrates (S1, S2, and S3) and volcanic ash, can be attributed to differences in their composition and physical properties. It is essential to recognize that each material was designed with specific characteristics and components to meet different requirements for green roof applications.

The commercial substrates (S1, S2, and S3) incorporate various components, including lapilli, pumice, zeolites, peat, slow-release fertilizers, and organic matter. These diverse compositions contribute to their unique thermal conductivity behaviors under different moisture conditions. For example, the presence of organic matter can affect thermal conductivity, especially when it becomes moist or saturated.

Table 5
Comparison of bulk density of different materials for the drainage layer.

Drainage material	Density [kg/m^3]	
	Dry	**Saturated**
Expanded clay	410.4	579.3
Perlite	164.2	510.5
Polyethylene	329.4	411.7
Volcanic ash	1043.0	1334.0

Note: Data of polyethylene are referred to recycled polyethylene granules (MAT1, MAT2, MAT3, MAT4, and MAT6)

Table 6
Comparison of thermal conductivity of different materials for substrate and drainage layer.

Material	**Thermal Conductivity [W/mK]**	**Dry**	**Moist**	**Saturated**
S1	Substrate	0.119	0.334	0.453
S2	Substrate	0.137	0.271	0.449
S3	Substrate	0.086	0.175	0.426
Volcanic Ash	Substrate	0.100	0.182	0.200
Expanded Clay	Drainage Layer	0.125	0.151	0.230
Perlite	Drainage Layer	0.076	0.087	0.297
Polyethylene	Drainage Layer	0.099	0.099	0.145
Volcanic Ash	Drainage Layer	0.100	0.182	0.200

Moisture content significantly influences the thermal conductivity of materials. The moisture conditions (dry, moist, and saturated) in this study were selected to represent the range of conditions that green roofs may experience in practice. The differences in thermal conductivity between volcanic ash and the commercial substrates can be partially explained by how these materials interact with moisture. For instance, volcanic ash may exhibit different moisture retention and heat transfer properties compared to substrates containing organic matter.

Another factor contributing to differences in behavior is the availability of local materials. The selection of materials for green roofs often considers local availability, which may result in variations in composition and, subsequently, thermal conductivity.

In summary, the variations in thermal conductivity observed in Table 5 can be attributed to the diverse compositions, moisture interactions, and local material availability associated with each material. This study aimed to assess volcanic ash as a potential alternative for green roofs, and while it exhibited competitive thermal insulation properties, it is essential to recognize that its behavior differs from commercial substrates due to these inherent material distinctions.

Table 6 provides a comparison of the thermal conductivity values for expanded clay, perlite, polyethylene, used in the drainage layer, as well as volcanic ash. The table presents thermal conductivity values for each material under three moisture conditions: dry, moist, and saturated.

The values presented in the table show how the thermal conductivity of each material is affected by its moisture content. It is evident that materials like perlite and volcanic ash experience notable changes in thermal conductivity as they become moist or saturated. On the other hand, expanded clay and polyethylene demonstrate more stable thermal conductivity values across different moisture conditions.

When designing drainage layers for green roofs, designers need to consider these thermal conductivity variations to ensure proper temperature control and energy efficiency within the structure. Materials with low thermal conductivity in both dry and moist conditions, like expanded clay and polyethylene, may offer better insulation properties, while those with significant increases in thermal conductivity when saturated, like perlite, may require careful attention in specific applications.

Overall, the table provides valuable insights into the thermal performance of different substrates used in green roofs, helping designers and researchers choose suitable materials based on the desired thermal properties for specific applications. Volcanic ash displays competitive thermal conductivity values in comparison to the tested substrates, suggesting its potential as a viable option for green roof applications.

4.3. Permeability

Permeability is a critical property that influences how efficiently water can flow through the material, affecting the overall drainage performance of the green roof system. Fig. 10 provides valuable information on the permeability characteristics of recycled polyethylene, perlite, expanded clay, and volcanic ash, either compacted or not.

The table demonstrates a considerable variation in permeability

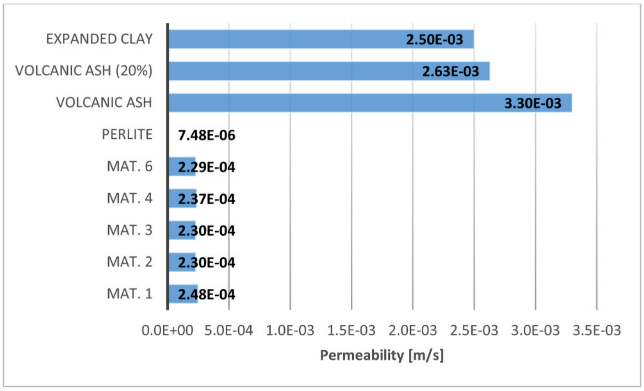

Fig. 10. Permeability of recycled polyethylene, perlite, expanded clay, and volcanic ash either compacted or not.

values among the different materials. At the lower end of the spectrum, there is "Perlite" with a permeability of 7.476E-06 m/s, indicating relatively low water flow through this material. On the other hand, the highest permeability values are observed for "Volcanic ash," with a value of 3.300E-03 m/s, which is significantly higher compared to the other materials, except for expanded clay, which shows a permeability of 2.5 E-03 m/s.

The permeability of recycled polyethylene ranges from 2.298E-04 m/s to 2.482E-04 m/s, showing relatively similar water flow characteristics. This suggests that the drainage performance of these plastic materials is comparable, and they can be considered as viable alternatives for the drainage layer.

The higher permeability of "Volcanic ash" is due to the presence of sand and gravel-sized particles, which create interconnected voids and facilitate efficient water drainage.

The permeability values presented have significant implications for green roof design. Materials with higher permeability, such as volcanic ash, offer better water drainage capabilities, which are essential for preventing waterlogging and ensuring the health of the vegetation on the green roof. On the other hand, materials with lower permeability, like perlite, might have limitations in terms of their drainage efficiency.

5. In-field experimental testing

Once the thermal and physical properties of volcanic ash have been determined, it is essential to assess vegetation development when using volcanic ash as a material for green roofs. For this purpose, green roof samples were installed in Giarre, a location near Catania, Italy (Fig. 11). The monitoring period for vegetation growth was from June 1, 2023, to September 1, 2023, during the summer season characterized by high outdoor temperatures, with maximum temperatures exceeding 40 °C, and no rainfall events, resulting in significant water stress on the vegetation.

Different green roof configurations were installed to compare vegetation growth on volcanic ash substrate (Ash) with that on a commercially used lightweight substrate for green roofs (Com) and with a substrate consisting of a mixture of volcanic ash and 5% by weight of commercial substrate (Ash+5%) to provide additional nutrients compared to the use of volcanic ash alone as a substrate.

Furthermore, various drainage layer materials were tested, including volcanic ash itself (Ash), expanded clay (Clay) as a commercial material, and recycled polyethylene granules (PE) obtained from the regeneration of plastic sheets used in agriculture for greenhouse covering and mulching. PE was considered an innovative material for the green roof drainage layer based on previous research.

Additionally, two sample sizes of green roofs were tested, with diameters of 18 cm and 28 cm. The irrigation system was programmed for daily watering at 5:00 p.m. for 5 min using a sprinkler system.

Regarding vegetation, four plant species suitable for extensive green roofs in a Mediterranean climate, namely *Phyla nodiflora*, *Myoporum parvifolium*, *Ficus repens*, and *Grevillea* were tested. Two plants of each species were installed in the 18 cm diameter samples, while three plants of each species were installed in the 28 cm diameter samples.

A filtering layer made of geotextile was placed between the substrate and the drainage layer to prevent substrate particles from clogging the drainage layer. Another layer of geotextile was placed at the base of the samples to prevent fine particles from the drainage layer from escaping the samples.

From the visual examination of the green roof samples, it can be observed that after a month and a half since the installation, which took place in early June, the commercial substrate already showed the appearance of initial weed growth. This is due to the addition of nutrients and fertilizers to the substrate to promote vegetation growth, which caused the rapid emergence of weeds. If not promptly removed, these weeds can cause irreparable damage to the planted vegetation. On the contrary, the substrates made with volcanic ash did not show any weed growth due to the absence of any type of fertilization.

However, thanks to the presence of nutrients and fertilizers in the commercial substrate, the vegetation development was better compared to the substrates made with volcanic ash. In particular, *Phyla nodiflora* and *Myoporum parvifolium* showed the best growth on the commercial substrate. On the other hand, *Ficus repens* and *Grevillea* do not seem to be significantly affected by the substrate difference, as they showed similar growth on the various tested substrates. *Grevillea* suffered particularly on the commercial substrate, indicating poor compatibility between this species and the composition of the commercial substrate.

It is important to note that after the summer period, characterized by high external air temperatures and no rainfall, thanks to the presence of the irrigation system, all tested vegetation species survived on the substrates made with volcanic ash. This demonstrates that volcanic ash can be a viable alternative to commercial substrates, although the vegetation development was slower and less vigorous compared to the commercial

Fig. 11. Green roof installation (31.07.2023, on the left – 12.09.2023, on the right).

substrates. Furthermore, this solution did not show weed growth, minimizing maintenance operations for the user and reducing costs throughout the lifecycle.

The absence of weed growth and the ability to support vegetation survival throughout different conditions highlight its potential as a sustainable and cost-effective option for green roof installations. With further optimization and experimentation, volcanic ash has the potential to contribute significantly to the advancement of green roof technologies, promoting environmentally friendly and resilient urban landscapes.

6. Future research and considerations

While this study has provided valuable insights into the thermal properties, physical characteristics, and permeability of volcanic ash for green roof applications, it is essential to acknowledge that the long-term durability of volcanic ash-based green roofs is a critical aspect that warrants further investigation. The durability of green roof materials is crucial to ensure their sustained performance over many years, and as such, future research endeavors should focus on conducting comprehensive durability assessments of volcanic ash-based green roofs.

To address this concern, future studies should include long-term monitoring and evaluation of volcanic ash-based green roof systems in real-world settings. This assessment can include factors such as material degradation, structural integrity, and the impact of weathering on the material's properties. Understanding how volcanic ash substrates and drainage layers perform over extended periods under varying environmental conditions will provide valuable data to assess their durability and potential maintenance requirements.

Another aspect that requires attention is the methodology for the proper installation of volcanic ash-based green roof systems. Developing practical guidelines and best practices for the correct placement and compaction of volcanic ash materials on rooftops is essential to ensure their optimal performance. Investigating installation techniques, load-bearing capacity, and the interface with other green roof components will contribute to the successful implementation of volcanic ash-based green roofs in practice.

Furthermore, future research should also include a comprehensive assessment of the environmental impact of utilizing volcanic ash in green roofs. Conducting life cycle assessments (LCAs) can provide a holistic view of the environmental benefits and potential drawbacks associated with this sustainable alternative. Assessing factors such as energy consumption, greenhouse gas emissions, and resource conservation will help in understanding the overall sustainability of volcanic ash-based green roof systems.

Lastly, future research should focus on integrating volcanic ash-based green roofs into architectural and urban planning frameworks. This involves collaboration between architects, urban planners, and environmental scientists to create designs that maximize the benefits of green roofs in terms of energy efficiency, urban heat island mitigation, and biodiversity enhancement. Investigating the aesthetic and functional aspects of volcanic ash-based green roofs within the broader context of urban design will contribute to the widespread adoption of this eco-friendly technology.

In summary, future research efforts should encompass a comprehensive evaluation of material durability, life cycle assessments, and the development of standardized installation methodologies. By addressing these aspects, it is possible promoting the effective and sustainable use of volcanic ash in green roof systems, advancing environmentally friendly and resilient urban landscapes.

7. Conclusions

In this study, the potential of volcanic ash as a sustainable green roof material was investigated, focusing on its thermal conductivity, physical properties, and permeability. The objective was to assess its viability as an eco-friendly alternative to conventional substrates. The key findings from this research reveal the following quantitative and comparative insights:

1. Thermal Conductivity: This study demonstrates a correlation between moisture content and thermal conductivity in volcanic ash. As moisture levels increase, thermal conductivity also rises. This trend was observed consistently, irrespective of the measurement method employed. For instance, the thermal conductivity values measured in the moist and saturated conditions were approximately 0.243 W/mK and 0.278 W/mK, respectively, indicating an increase from the dry state's value of 0.125 W/mK. This quantitative information highlights the material's improved heat conduction capabilities as it becomes saturated, with implications for green roof thermal performance.
2. Particle Size Distribution: Volcanic ash primarily comprises sand and gravel-sized particles, contributing to its favorable porosity and permeability. The dominance of these larger particles enables efficient water movement through the material, facilitating proper drainage on green roofs. Additionally, the presence of gravel-sized particles enhances structural stability and load-bearing capacity, ensuring resilience to external forces such as wind and foot traffic. The limited proportion of silt-sized particles further confirms the material's suitability for green roof applications. This quantitative characterization provides data supporting its application in green roofs.
3. Permeability: The permeability tests yielded quantitative results that are crucial for green roof design and functionality. At 0% compaction, reflecting the material's initial state on a green roof, a permeability of 0.0033 m/s was measured. This quantification demonstrates the material's capability to efficiently drain excess water, preventing waterlogging and supporting robust vegetation growth. In contrast, at the 20% compaction level, simulating increased compaction forces from factors such as heavy rainfall or foot traffic, the measured permeability was 0.0026 m/s. While this value indicates a reduction compared to the 0% compaction scenario, it remains within an acceptable range for green roof applications. These quantitative permeability values provide specific guidance for green roof designers and builders.
4. Weed Resistance: While this study confirmed resistance to weed growth in volcanic ash substrates, it's important to note that commercial substrates exhibited superior vegetation development due to their nutrient content. This quantitative comparison underscores the need for additional research to optimize the nutrient content of volcanic ash-based substrates for enhanced vegetation growth on green roofs.

In conclusion, this research offers quantitative and comparative insights into the suitability of volcanic ash as a sustainable green roof material. These findings include the correlation between moisture content and thermal conductivity, the quantitative characterization of particle size distribution, permeability measurements at different compaction levels, and a quantitative comparison of weed resistance with commercial substrates. The inclusion of these quantitative results provides valuable data for architects, engineers, and researchers seeking to harness the full potential of volcanic ash in green roof systems. Further research should focus on optimizing volcanic ash substrates to address specific challenges and maximize their performance in green roofs.

CRediT authorship contribution statement

Gagliano Antonio: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Cascone Stefano:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation.

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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