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Article

Albedo of Pervious Concrete and Its Implications for Mitigating Urban Heat Island

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Abstract: Urban heat islands have become a growing concern in many cities around the world. Pervious pavements have been proposed as a potential solution to mitigate this effect, but their effectiveness in reducing surface temperatures is still uncertain. This experimental study aims to investigate the reflectivity of pervious concrete to determine whether pervious pavements are cooler than conventional pavements. To achieve this, five different Portland cement concrete mixes are used to create pervious concrete samples with varying porosity levels. The samples are sliced, and their spectral reflectance and albedo are measured and analyzed. The results showed that the albedo of dry pervious concrete decreases linearly with increasing porosity. Pervious concrete with a wet surface exhibits an albedo of approximately 0.15 which is independent of porosity. Additionally, fresh, dry pervious Portland concrete has an albedo ranging from 0.20 to 0.35, which is 0.10 to 0.20 lower than conventional fresh cement concrete. As a result of this low albedo, caution should be exercised when developing pervious concrete as a solution to combat the urban heat island effect, unless measures are taken to increase evaporation and offset the additional solar absorption resulting from the low albedo. Overall, these findings suggest that the use of pervious pavements alone may not be sufficient to reduce surface temperatures in urban areas. Future research should explore ways to increase the albedo of pervious pavements and develop effective strategies to mitigate the urban heat island effect.

Keywords: Portland cement concrete; spectral reflectance; evaporation; solar absorption; urban heat island

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1. Introduction

The thermal environment of a city refers to the temperature and heat patterns within an urban area. The urban heat island (UHI) effect is a phenomenon where urban areas experience higher temperatures compared to the surrounding rural areas [1]. This is due to the increased amount of human activity, such as the construction of buildings and roads, which absorbs and radiates heat [2]. The thermal environment of a city can have significant impacts on the health and well-being of its residents [3–5]. High temperatures can lead to heat-related illnesses, particularly in vulnerable populations such as the elderly and young children [6]. Additionally, increased energy use for air conditioning can contribute to higher greenhouse gas emissions, exacerbating climate change [7–10]. Therefore, understanding and improving the urban thermal environment is critical for promoting the health and well-being of its residents, as well as mitigating the impacts of climate change.

In recent decades, a great many studies have been conducted on strategies such as changing the urban geometry, planting vegetation, and utilizing cool materials, as well as incorporating bodies of water for improving the urban thermal environment [7,11].

Although existing applications do play a role in improving the urban thermal environment, the proposed effective measures have not been widely applied due to the restrictions of policies, costs, technical conditions, and other factors.

Pervious concrete is produced using a single-graded coarse aggregate and cement/asphalt binder, which has a porous structure, allowing water to pass through it and infiltrate the soil beneath [12]. It is reported that there are a number of obvious advantages to the application of pervious concrete such as managing stormwater runoff and reducing the risk of flooding, promoting vegetation growth, improving the quality of air and water, and providing long-term cost saving over conventional concrete [13–15]. Based on these features of pervious concrete, it has been widely used in pavement engineering, which is seen as a sustainable and effective solution for improving the thermal environment of the city. Similarly, Pervious pavements are created with the intention of facilitating stormwater percolation through their cavities, which helps recharge the groundwater [13,16–18]. The cavities in pervious pavements can retain some of the water that passes through them. This retained water may evaporate during the subsequent drying period, which has the potential to lower the pavement temperature. As a result, pervious pavements have been identified as a potential solution to mitigate the urban heat island effect [14,19–21].

In order to implement pervious pavements as a measure to mitigate the urban heat island effect, designers must have a thorough understanding of whether the thermal properties of pervious concrete make these pavements cooler than traditional dense pavements. Among these properties, the reflectivity, also known as albedo, of pervious pavements is a crucial property, as the amount of solar absorption is dependent on the product of the albedo and solar irradiation. The porosity, water absorption, permeability, evaporation, mechanical strength, and design of pervious concrete have been the focus of many studies [15,18,22–33] to verify that pervious concrete acting as a pavement material is an alternative to improve the thermal environment and even mitigate the urban heat island effect in urban areas. Among these studies, Yang et al. [30] conducted an experimental study on the performance of pervious concrete pavement materials and the results showed that using silica fume and superplasticizer, as well as the organic polymer can enhance the strength of pervious concrete which can reach 50 MPa in compressive strength. It is also reported that the pavement materials used in the study have a good performance in terms of water penetration, abrasion resistance, and freezing and thawing durability. Wang et al. [31] investigated the water absorption capability and evaporation cooling effect of pervious paving materials and found that evaporation does very little to decrease the surface temperature of pervious pavement materials. Sičáková et al. [32] clarified the relationships between functional properties of pervious concrete, which can help to predict some properties of pervious concrete. Qin et al. [33] found that incorporating a small amount of pulverized biochar into pervious concrete can improve the mechanical strength and absorption, as well as enhance the evaporation of pervious concrete. However, limited attention has been given to the spectral reflectance and albedo of pervious concrete [34]. The porous surface of pervious concrete may exhibit a different absorptivity compared to the concrete matrix, which could result in a different albedo to that of dense concrete. Additionally, the presence of moisture on the surface of pervious concrete can alter the surface color and therefore affect the albedo. Furthermore, pervious concrete is prone to clogging, which can reduce its porosity over time [35,36]. In summary, the effect of the reflectance or albedo of pervious concrete on urban thermal environment and its mechanism are still not understood well. Thus, it is crucial to characterize the albedo of pervious concrete and to assess how this albedo is affected by porosity and surface wetness/dryness.

This experimental study investigates the spectral reflectance and albedo of pervious Portland cement concrete with varying porosity and wet/dry surfaces. Considering that the porosity of pervious concrete is generally about 15–35%, here, five Portland cement concrete mixes with different amounts of sand as the filler are cast, producing pervious concrete samples with varying target porosity from 0.15 to 0.35. The porosity and water absorption of the samples are determined. The samples are then sliced and analyzed using a spectrophotometer to measure their spectral reflectance. It is worth noting that in this study, the term "pervious concrete" specifically refers to pervious Portland cement concrete pavement unless explicitly stated otherwise.

2. Materials and Experiments

2.1. Mix Proportions and Sample Preparations

Five pervious concrete mixtures consisting of Portland cement, water, and coarse aggregates were prepared. Ordinary Type I Portland cement was used. The coarse aggregate is made of crushed limestone with a single gradation ranging from 5 mm to 10 mm. This aggregate has an absorptivity of 0.55%, an observed density of 2725.7 kg/m^3, and a bulk density of 1452.1 kg/m^3. A cement/aggregate ratio of 1:4 was used by weight. To make pervious concrete samples of differential porosity, different amounts of fine sand were used as filler. The fine sand used in this experiment has an average size of 0.25–0.3 mm and a fineness modulus of 2.2. Table 1 provides details of the mixed components, including the weight ratios of sand to aggregate, which are 0.1, 0.2, 0.3, and 0.4, respectively. The sand used in the mixture has a white-brown color, and its reflectivity was measured to be approximately 0.45 according to ASTM E1818A.

Table 1. Mix proportion used to produce the five pervious concrete mixtures.

No.	Sand Ratio	Mixture Proportion (kg/m^3)							Target Porosity ϕ
		w/c Ratio	Cement	Fly Ash	Aggregates	Sand	WRA	Water	
1	0.0	0.28	240	60.06	1501	0	2.40	123	0.35
2	0.1	0.28	243	60.76	1367	152	2.43	124	0.30
3	0.2	0.28	246	61.47	1229	307	2.46	126	0.25
4	0.3	0.28	249	62.20	1089	467	2.49	127	0.20
5	0.4	0.28	252	62.95	944	630	2.52	129	0.15

Notes: WRA in the table stands for water reducing agent.

To create the selected mixtures, a 0.05 m^3 rotating-drum mixer was used. The mixing process was begun by adding the aggregate to the mixer, followed by pouring the estimated amount of water needed to wet the aggregate surface for 1 min. Next, the cement was added to the mixer, and the materials were mixed for another min. Finally, the required amount of water needed to achieve the desired water-to-cement ratio was added to the mixer and mixed for an additional 2 min. The resulting concrete mixtures were poured into slender wood molds with dimensions of 150 × 150 × 860 mm^3. To ensure consistent compaction in each layer, all mixtures were gently rodded 10 times across three layers. Additionally, spatulas were used to level the mixtures in the molds without the application of any vibration. All the mixtures were cast into prepared molds in a short time at an ambient temperature of 25 ± 2 °C, and then they were transferred to a foggy room with a temperature of 20 °C and a relative humidity exceeding 95% for a 3 day curing period. Following this, they were de-molded and relocated to the same air-conditioned room for an additional 25-day curing period. Each cured block was drilled for six cores with a diameter of 100 mm and a length of 100 mm.

The drilling debris was removed from the cores through vacuum-washing before submitting them to porosity measurement. Equation (1) is used to determine the porosity (ϕ) of the pervious concrete samples.

$$\phi = 1 - \frac{(w_2 - w_1)}{dV} \tag{1}$$

where w_1 (kg) is the sample weight under water, w_2 (kg) is the oven-dry sample weight; d (kg/m^3) is the density of water at room temperature; and V (m^3) is the volume of the sample. First, the sample was dried in an oven at 105 °C for 1.5 h and allowed to cool to room temperature before the oven-dry weight w_2 was measured. Next, the sample's weight w_1 was determined by submerging and stirring the sample under water until all the embedded air bubbles were released. The volume of the sample was obtained by measuring the length and diameter of each sample three times using a Vernier Caliper, and the average of the three measurements was taken as the sample's dimension.

The water absorptivity, α, was measured according to the following procedure. Each sample was first weighted in room-dry condition to get m_d. The samples were then immersed under water for 24 h, before being taken out and left above a sieve until no water dripped from the bottom of the samples. The weight, m_w of the wet sample was measured. The ratio of the weight difference between the dry and wet conditioned cement to the weight of the dry sample is deemed the water absorptivity of the samples.

The water absorption, α, of the sample is determined by Equation (2).

$$\alpha = \frac{(m_w - m_d)}{m_d} \tag{2}$$

where m_w (g) and m_d (g) are the weights of the sample at wet and dry stages, respectively.

2.2. Albedo Measurements

Figure 1a illustrates how some of the cored samples were sliced into round-plane samples with a thickness ranging from 0.5 to 1.0 cm. For each mix, three representative slices were chosen along with a dense cement concrete slice sample. The aggregate of the dense sample is limestone, but the water-to-cement ratio remains unknown. Once sliced, all samples were vacuumed and left to dry at room temperature for one day.

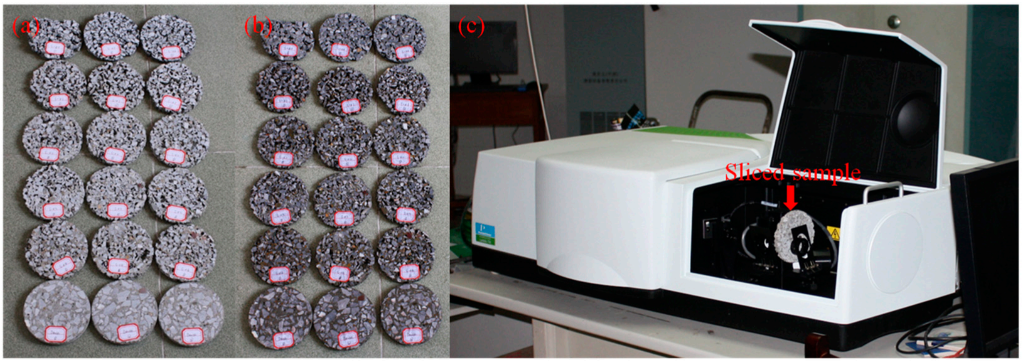

Figure 1. Sliced samples prepared for spectral reflectance test (**a**) Sliced samples with dry surface (**b**) Sliced samples with wet surface (**c**) Spectrophotometer Lambda 750. (Lambda 750 Spectrophotometer is manufactured by PerkinElmer, a company based in the United States, and produced in Shanghai, China).

A total of 12 dry samples were analyzed for spectral reflectance measurements as depicted in Figure 1. To minimize experimental errors, we employed a Lambda 750 spectrophotometer (Figure 1c) to measure the spectral reflectance of each sample six times, and we selected three measurements that exhibited similar spectral reflectance values as the measured reflectance. The spectral reflectance, denoted as $R(\lambda)$, represents the reflectivity of a surface across different irradiance wavelengths (λ = 200 nm~2.5 µm). The corresponding albedo, ρ, can be calculated using Equation (3).

$$\rho = \frac{\int_{\lambda_0}^{\lambda_1} R(\lambda) \times I(\lambda) d\lambda}{\int_{\lambda_0}^{\lambda_1} I(\lambda) d\lambda} \tag{3}$$

where λ_0 = 0.2 µm and λ_1 = 2.5 µm; $I(\lambda)$ is the spectrum of solar irradiance reaching the earth's surface. This study set $I(\lambda)$ as the standard solar irradiance, which can be found by referring to ASTM E892.

After the spectral reflectance at dry conditions was measured, the sliced samples were immersed in water for 24 h and then taken out and wiped with a towel so that no water bubbles were visual on the sample (Figure 1b). The wet sample was then submitted to the Lambda 750 spectrophotometer (Figure 1c) to test the spectral reflectance.

3. Results

3.1. Porosity and Water Absorptivity

Figure 2 illustrates the porosity measurements of the pervious concrete samples with varying sand ratios. Three samples were tested for each sand ratio, resulting in some deviations in the measured porosity. However, the average porosity of the samples decreases linearly with increasing sand ratio, as shown in the figure. This phenomenon can be explained by the filling effect of the fine sand, which has an average size ranging from 0.25–0.3 mm. A large number of pores will be filled by the sand particles as the sand ratio increases, which is attributed to the particle size gradation of the sand used in this study being smaller than that of coarse aggregates, resulting in the porosity of the pervious concrete samples decreasing.

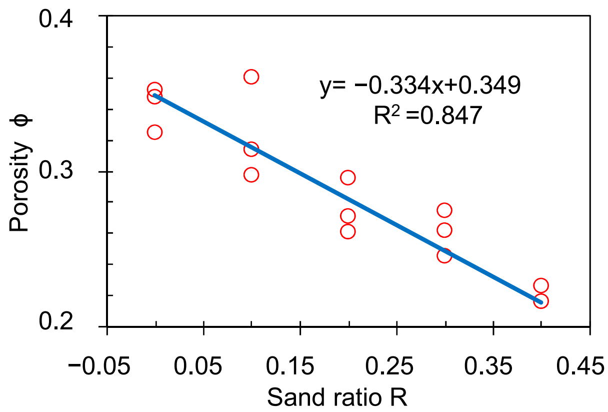

Figure 2. The porosity of pervious concrete samples with different sand ratios.

Figure 3 displays the water absorptivity of the pervious concrete samples with different porosity. Despite the porosity ranging from approximately 0.15 to 0.35, the water absorptivity appears to be less influenced by the porosity, as indicated by the low confidence of the linear correlation between absorptivity and porosity (Figure 3, $R^2 = 0.128$), a phenomenon that is coincident with the findings of the study in Ref [33]. This may be due to the non-absorptive nature of the sand filler, which does not affect the absorptivity. Generally, the water absorption of pervious concrete primarily depends on the absorption of cement binder, which can be regarded as a constant in this study according to the mix proportion. In addition, the high porosity of the pervious concrete sample is controlled by the large pores between aggregates, which cannot retain water. Consequently, the relationship between porosity and absorption is not significant as is shown in Figure 3. The weight-based absorptivity is approximately 1% to 2%, a percentage that is consistent with previous observations [37].

3.2. Spectral Reflectance and Albedo

Spectral reflectance refers to the ratio of the amount of light reflected by a surface at each wavelength to the amount of light incident on that surface at each wavelength. In other words, it is the measure of how much light of each color is reflected by an object. Conversely, albedo is a measure of the fraction of incident radiation reflected by a surface, typically expressed as a percentage. It is a measure of the overall reflectivity of a surface.

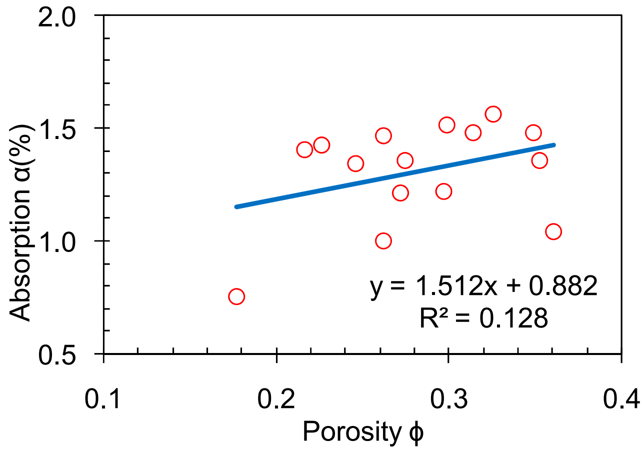

Figure 3. The relationship between water absorption and porosity of the pervious concrete samples.

Practically, the surface of pervious concrete can stay wet or dry. A wet surface looks darker than a dry surface. Understanding the spectral reflection on these different surfaces is important to predict the pavement surface temperature, which could make a big difference in mitigating the urban heat island effect.

3.2.1. Spectral Reflectance of Pervious Concrete Samples

Figure 4a presents the measured spectral reflectance of pervious concrete samples with different sand ratios and different dry/wet surfaces, as well as dense samples. To simplify the data presentation, the spectral reflectances of samples with the same sand ratios are averaged. The results show that the reflectance increases as the sand ratio increases, which is to say that the reflectance decreases as the porosity increases according to the previous analysis (Section 3.1). This is because, when solar radiation reaches the cavities, the reflected radiation may be absorbed by the cavity walls instead of returning to the sky. As a result, cavities at the surface of pervious concrete can be considered black spots, which decreases the reflectance with an increase in porosity. The addition of sand as a filler reduces the cavity size, and more radiation reaching the filler tends to be reflected back to the sky.

Regarding spectral reflectance, dry surfaces show more reflectance in ultraviolet and visible light than in infrared light. This difference may be attributed to the absorptivity of the cavities on the surface of the sample, which is greater for ultraviolet and visible light due to their shorter wavelengths. In contrast, infrared light has longer wavelengths and can cross the barriers of small cavities with less absorptivity. In fact, reflectance and porosity are strongly related, particularly when it comes to visible and infrared light. Porosity refers to the amount of empty space within a material, while reflectance refers to the amount of light that is reflected from the surface of that material. In general, materials with higher porosity tend to have lower reflectance, particularly in the visible spectrum of light. This is because when light hits a porous surface, it is scattered and absorbed more readily, which reduces the amount of light that is reflected back to the observer. In the infrared spectrum of light, the relationship between reflectance and porosity is more complex. In some cases, materials with higher porosity may have higher reflectance in the infrared range due to the presence of air voids, which can act as insulators and reduce heat loss. However, in other cases, the opposite may be true, with more porous materials having lower reflectance due to increased scattering and absorption of infrared radiation. It's important to note that the relationship between reflectance and porosity can also be influenced by other factors, such as the size and shape of the pores, as well as the composition and structure of the material itself.

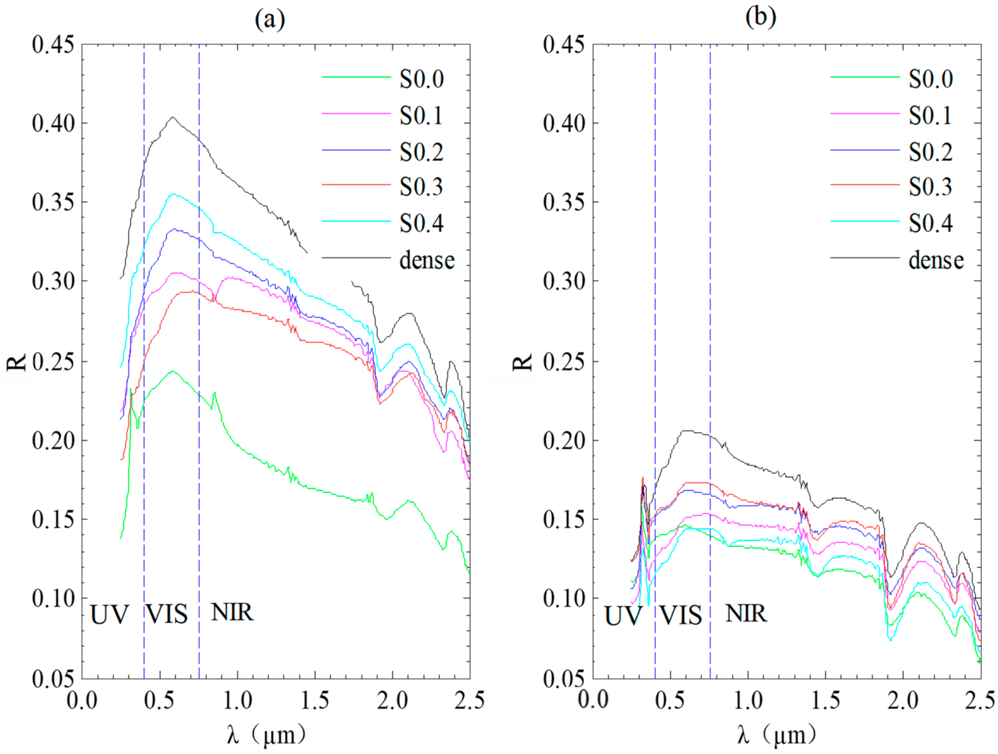

Figure 4. Spectral reflectance, *R* (-), of the pervious concrete with different sand ratios, (**a**) at dry condition; (**b**) at wet condition.

Figure 4b illustrates the spectral reflectance of samples with wet surfaces. The results show that the reflectance is about 0.10–0.20 lower than that of dry samples. In the wet state, the influence of porosity on the reflectance is less distinct than that in the dry state. This may be because, in the wet state, the surfaces of the aggregate and paste appear dark and have absorption similar to that of cavities on the surface of the samples.

3.2.2. Albedo of Pervious Concrete Samples

Compared to spectral reflectance, pavement engineers pay more attention to the albedo of a pavement surface [38]. Albedo (ρ) is the fraction of solar radiation reflected from the earth's surface back into space. The albedo can be computed by using Equation (3), in which the incident solar radiation is the solar radiation at sea level. Figure 5 shows the albedo of the pervious concrete samples and of dense concrete samples. The porosity of the dense samples is unknown and we assumed they have a typical porosity of 8%.

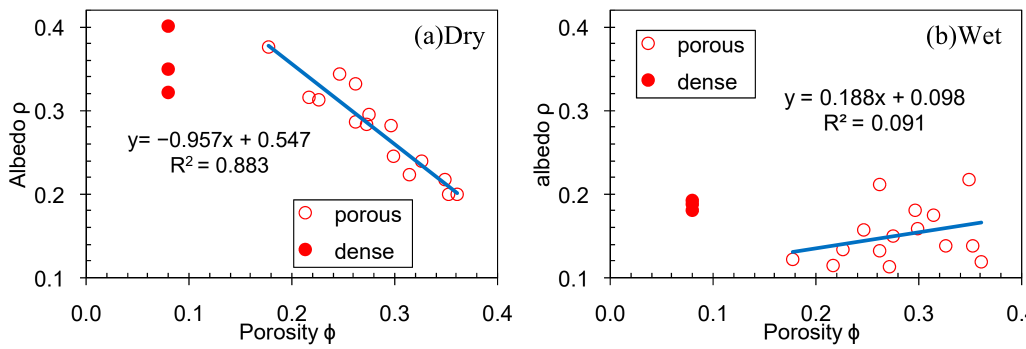

Figure 5. The albedo of pervious concrete with different porosity and dry/wet surface.

Figure 5a demonstrates that, when the samples are dried, the albedo decreases linearly as the porosity increases. The slope of the descending line is 0.957, which implies that a porosity increase of 0.10 would cause a 0.10 reduction in the albedo. Pervious concrete typically possesses a porosity ranging from 0.15 to 0.30, which is 0.10 to 0.20 greater than the porosity of traditional dense concrete. Consequently, the albedo of pervious concrete is generally 0.10 to 0.20 lower than the albedo of dense concrete.

When the samples are wet, the albedo is low and is insensitive to the variation in the porosity. The albedo in a wet state varies from 0.10 to 0.20, which is 0.10–0.20 lower than the albedo in a dry state. The dense samples have the same small albedo as the pervious samples, suggesting that the wet surface rather than the porosity dominates the albedo of the surface. This dominance can be inferred from the albedo of the dense samples. The albedo of dense samples exhibits a high deviation when dry but is merged when wet (Figure 5b), further implying that the wet condition dominates the albedo of the surface.

4. Discussion

Urban thermal environment, which is closely related to residents' happiness, comfort, life, and health, has attracted more and more attention. Outdoor thermal comfort influenced by the outdoor thermal environment plays an important role in daily life, and residents in urban areas expect their comfort to improve. Accordingly, there is an urgent need to study and apply new and effective technical means to improve urban thermal comfort by alleviating the urban heat island effect.

Pervious concrete has been proposed as a possible solution to mitigate the urban heat island effect by using internal pores and water-retaining materials to hold rainwater for evaporative cooling during hot, dry summer days. In the hot and rainy season, pervious concrete is expected to be an alternative to infiltrate the rainwater, retain the rainwater, as well as make pedestrians more comfortable by the evaporative cooling effect, which seems like a perfect application without any drawbacks in practical engineering. However, it is worth noting that based on both field and laboratory measurements, it has been established that the evaporation of pervious concrete has a minimal effect on the evaporative cooling of pervious pavements, particularly one to two days following wetting, as reported in [15,31,39–41]. Surprisingly, pervious concrete tends to have higher surface temperatures than conventional concrete during the daytime but lower temperatures during nighttime. It has been predicted that pervious hot-mix asphalt pavements would exhibit the highest daytime surface temperatures and lowest nighttime temperatures relative to pervious cement concrete and dense concrete [42], which indeed decreased the thermal comfort in urban areas during the daytime.

The observed hot surface temperatures of pervious pavements are due to the fact that, in dry conditions, pervious concrete has lower reflectivity and a tendency to absorb more solar radiation compared to dense concrete. Specifically, the albedo of dry pervious concrete is approximately 0.10–0.20 lower than that of dense concrete, resulting in an additional solar absorption of approximately 100–200 W/m^2 during the middle part of a typical summer's day [43]. This additional heat gain is several times higher than the heat loss induced by the evaporative cooling effect because the water absorption of pervious concrete is very low (Figure 3). The evaporation of pervious concrete during the middle part of a summer's day contributes only about 33–47 W/m^2 or even lower [44,45]. Consequently, pervious pavements receive additional heat compared to dense pavements. Due to the fact that porous concrete has lower heat volumetric capacity and thermal conductivity than dense concrete, any heat gain tends to increase the surface temperature of pervious concrete. As a result, pervious pavements tend to be hotter than dense pavements unless additional heat gain at the surface caused by the low albedo is compensated for by increasing evaporation [40,46]. Therefore, it is important to exercise caution when developing pervious concrete with the goal of mitigating the urban heat island effect.

Evaporation is enhanced when the surface of pervious concrete is wet. As the water absorptivity of pervious concrete is very low (Figure 3), keeping the surface wet can be achieved by using water-absorptive fillers to suck water from deeper layers to the surface, which is achieved through the design of water-retentive pavements [33,37,47,48].

However, the albedo of wet pervious concrete surfaces is about 0.10–0.20 lower than that of dry dense concrete. Therefore, the design of water-retentive pavements must promote sufficiently high evaporation to overcome the additional solar absorption caused by the lower reflectance on the wet surface. Based on these findings, further research is urgently needed to study the synthesis of reflective-evaporative-pavement materials, which could reflect more heat into the sky and obtain full use of cooling by evaporation simultaneously.

5. Conclusions

In this paper, we provide an experimental study on the porosity, absorption, reflectance, and albedo of pervious Portland concrete with different sand ratios, placing emphasis on the variation in reflectance and albedo with different distributions of porosity under dry and wet conditions. The main conclusions drawn from this investigation are summarized as follows:

(a) Due to the filling effect of fine sand used in this study, the porosity of the pervious concrete samples decreases linearly with an increase in sand ratio. Differently, the water absorption of the pervious concrete samples is less influenced by changes in porosity, because the absorption by the samples primarily depends on the absorption by the cement binder and only a little on the porosity.

(b) Pervious Portland concrete exhibits an albedo of approximately 0.20 to 0.35 under dry conditions, which is 0.10 to 0.20 lower than the albedo of dense Portland concrete. This reduction in albedo is due to the absorptive nature of cavities on the surface of pervious concrete, resulting in a linear correlation between porosity and albedo under dry conditions. However, this relationship does not hold for wet pervious concrete, which exhibits an albedo of approximately 0.10 to 0.20, similar to that of wet dense concrete.

(c) The lower reflectivity of dry pervious concrete surfaces results in additional solar absorption during the middle part of a typical summer's day, compared to dry dense concrete. As a result, caution must be exercised when developing pervious concrete to mitigate the urban heat island effect. Further studies are expected to deeply comprehend the albedo of pervious asphalt concrete, the variation in the albedo of pervious pavement over time, as well as novel materials which can increase the albedo of pavements without losing the original properties.

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