Evaluating the Thermal Performance of Permeable Pavements: A Case Study in an Urban Area of Vietnam

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Abstract

In urban areas with a high degree of concrete urbanization, the urban heat island (UHI) effect has become an environmentally significant concern. Among UHI factors, the materials that cover the ground surface significantly affect temperature variation in urbanized areas. Several solutions have been implemented for mitigating the increase in ground surface temperatures, including the use of materials with self-cooling capabilities such as water-permeable (pervious) interlocking blocks, asphalt and concrete. In particular, surfacing with the pavements using water-permeable interlocking blocks and concrete supplemented with water-retaining materials has been employed to enhance the effective reduction of ground surface temperatures under hot summer climate conditions. The objective of this study is to evaluate the thermal performance of water-permeable surface pavers in car parking lots in Hanoi, Vietnam. Various water-permeable pavement structures were applied in the test areas for on-site testing. Pervious concrete (PC), which included recycled materials from construction waste, natural aggregates and fine lightweight aggregate from autoclaved aerated concrete (AAC), was utilized with variations in ground surface temperature monitored. Additionally, ground surfaces using both asphalt concrete and conventional concrete were tested for comparison. During the on-site monitoring conducted in the summer, all water-permeable pavements contributed to surface temperature reductions of over 5°C. Remarkably, the surface temperature of water-retaining PC using AAC was more than 10°C lower when the surface temperature of asphalt concrete reached nearly 60°C. This paper also reports results on the mechanical properties and permeability coefficients of water-permeable pavements.

Key words: permeability coefficient, recycled aggregate, surface temperature, water-permeable pavement

1. Introduction

The process of urbanization increases the area of surface covered with materials such as concrete, asphalt, various types of tiles, and natural or artificial stones and contributes to local flooding phenomena. The rapid reduction of groundwater levels can lead to subsidence and water resource depletion. Additionally, 90% of the temperature increase in urban areas is attributable to the heat-absorbing and retaining properties of the construction materials (Ferrari *et al.*, 2020). In the development strategy for Hanoi, Vietnam, the significant role of using permeable surfaces to mitigate the UHI effect has been emphasized (PM, 2008; Duc Ha, 2022). The use of PC as a water-permeable material has been recognized by the U.S. Environmental Protection Agency (EPA) as one of the most effective methods for managing storm water (EPA, 2012). It has also been confirmed as an efficient material for mitigating the UHI effect (Higashiyama *et al*., 2016).

PC typically uses course aggregates from a variety of sources (ACI 522.R-10, 2010). In Vietnam, economic and social development has accelerated construction and infrastructure investment, resulting in a substantial volume of construction and demolition waste (CDW) (MONRE, 2011, 2018). Recycled aggregate (RA) materials from CDW have gained attention and are being used as substitutes for natural aggregates. Among them, the use of RA to make PC has become popular and widely applied in research. Japan and several European countries have achieved recycling rates for CDW exceeding 98% (Tam *et al*., 2010; Söderholm, 2011), while the ratio of CDW recycling and reuse remains relatively low in Vietnam.

PC utilizing RA can take advantage of the water-absorption and retention characteristics of certain RA types such as AAC. The use of water-absorbing and water-retaining aggregates in the production of PC, known as “cool pavements,” takes advantage of the water evaporation process. Numerous researchers have been investigating and utilizing PC as a surface layer in permeable pavement systems (PPS) (Qin, 2015; Kousis and Pisello, 2023).

PPS systems are defined as complete systems consisting of surface, base, sub-base and roadbed layers, plus water collection systems (if applicable). PPS is widely applied to light-traffic-load roadways, parking lots and sidewalks (Tijani and Ajagbe, 2018). Kayhanian *et al.* (2012) noted that most PC applications are in parking lots with restricted load-bearing requirements. The typical design thickness for parking lots (with no heavy loads) in the United States ranges from 125 to 300 mm (ACI 522.R-10, 2010). The application of PPS is currently not common in many developing countries, such as Vietnam, where traditional drainage systems are inefficient and overloaded (Japan Road Association, 2007). Based on the analyses presented above, this paper proceeds to evaluate the effectiveness of using PPS systems in reducing the surface temperature of PC surfaces, thus contributing to mitigation of the UHI effect. The surface temperature of PC is compared to those of other surfaces to prove the effectiveness and role of water-retaining materials. Additionally, the permeability coefficient and compressive strength of PC surfaces after two years of use are studied.

2. Methodologies

The PC used in this study was designed and implemented experimentally in parking areas at the Hanoi University of Civil Engineering (HUCE) and DEEP C (Hai Phong) (Figs. 1 and 2). This study focused on evaluating the test area in Hanoi (HUCE). Four different types of PCs were used, with various other surfaces such as asphalt concrete and concrete tiles serving as reference materials. The PPS structure was designed to include three layers: a blended sand and soil layer, a foundation layer (base course), and a surface layer (Table 1). Table 2 presents the mix design of surface layers. Table 3 gives information on physical properties of the surface layers used in this study. The specifications for this parking lot structure are suitable for vehicles with a load capacity of up to nine seats. The primary material of the base layer is recycled concrete aggregate with particle sizes up to 40 mm and gradations of 0–5 mm, 5–10 mm, 10–20 mm, and 20–40 mm conforming to TCVN 13694–2023 standards.

The experimental construction process was carried out in the following steps: (1) Site preparation: removing the existing material layers and compacting the soil base to ensure the subgrade meets the design specifications. (2) Base layer construction: laying down the base layer

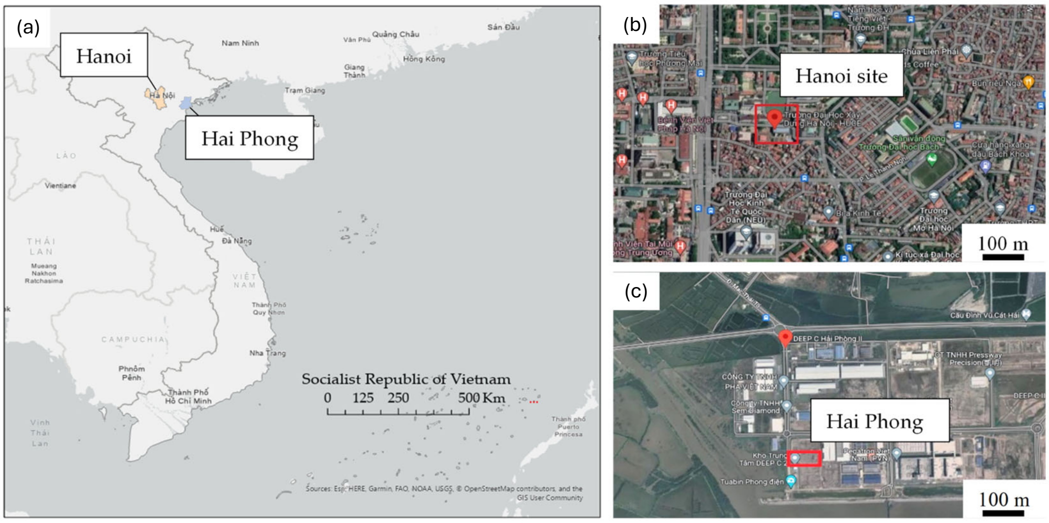

Fig. 1 (a) Location of Hanoi and Hai Phong cities. The tested sites at (b) Hanoi City (inside the campus of Hanoi University of Civil Engineering) and (c) Hai Phong City (inside one of the Deep C Industrial Zones). Base Map data: OpenStreetMap and GISuse of Glethm Communications, and © 2023 Google.

according to the design, ensuring proper compaction. (3) Concrete mix preparation: mixing the concrete in batches using a 250-liter forced concrete mixer, and immediately

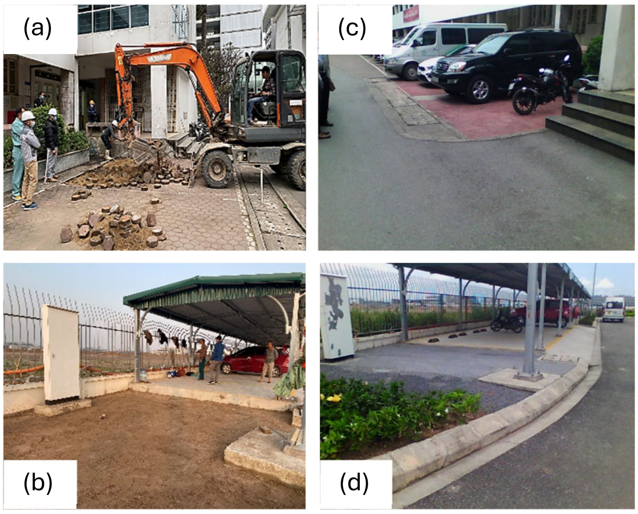

Fig. 2 Construction of tested sites in Hanoi (a, c) and Hai Phong (b, d) .

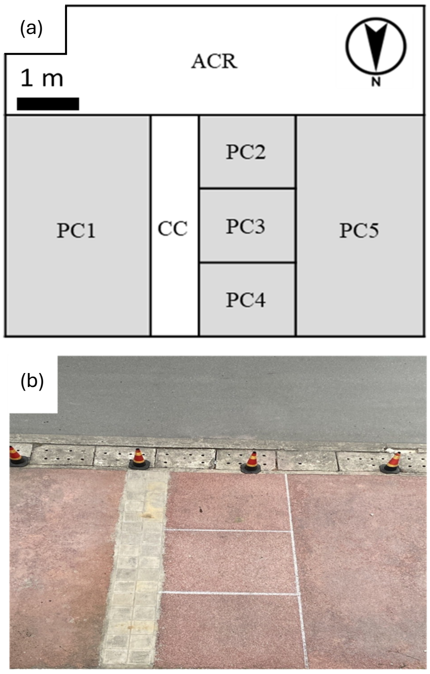

Fig. 3 Layout information on types pavements examined in this study in Hanoi.

Table 1 Compositions and structures of the pavements in this study.

Type	Layer	Composition and structure	Thickness (cm)
PC1	Surface course	Pervious concrete (RCA 50% + NA 50%)	10 (parking lot)
	Base course	Graded RCA with $D_{max} = 40$ mm	15 (parking lot)
	Subgrade	Sandy soil	> 30
PC2	Surface course	Pervious concrete (RCA 100%)	10
	Base course	Graded RCA with $D_{max} = 40$ mm	15
	Subgrade	Sandy soil	> 30
PC3	Surface course	Pervious concrete (RCA 90% + AAC 10%)	10
	Base course	Graded RCA with $D_{max} = 40$ mm	15
	Subgrade	Sandy soil	> 30
PC4	Surface course	Pervious concrete (RCA 90% + AAC 10%)	10
	Subgrade	Sandy soil	> 40
PC5	Surface course	Pervious concrete (NA 100%)	10
	Subgrade	Sandy soil	> 40
CC	Surface course	Conventional concrete (RCA)	4
	Subgrade	Sandy soil	> 40
ACR	Surface course	Asphalt	10
	Base/Subase/Subgrade	-	-

Table 2 Mix design of surface pavements in this study.

Mixing information			PC1	PC2	PC3	PC4	PC5	CC	ACR
Item	Symbol	Unit							
Max. size of aggregate	D_{max}	mm	10	10	10	10	10	20	12.5
Ratio of water to cement	W/C	%	0.33	0.33	0.33	0.33	0.33	0.56	-
Ratio of sand to aggregate (by weight)	S/G	%	53	-	6.8	6.8	-	40.7	55.3
Air volume	A	%	18	20	20	20	20	3.3	4.5
Mass of unit volume (m^3)									
Water	W	kg	110	111	111	111	111	196	-
Cement	C	kg	361	337	337	337	337	350	-
Coarse aggregate (> 5 mm)	G	kg	658	1317	1090	1090	1525	947	1305
AE water-reducing agent	–	ml	1444	1011	1011	1011	1011	-	-

Table 3 Physical properties of the surface layers used in this study.

Composition	Porosity (%)	Dry density (kg/cm^3)	Water content[*] (%)	Thermal conductivity [W/(m·K)]
RCA 50% + NA 50%	18	1,850	5.7	0.69
RCA 100%	20	1,706	8.3	0.68
RCA 90% + AAC 10%	20	1,684	14.5	0.70
NA 100%	20	1,905	2.6	0.74
CC	1.5	2,360	2.9	0.4–1.5 (typically 1.2)[**]
ACR	3.2	2,413	1.7	1.35 – 2.1 (typically 1.7)[***]

[*] Gravimetric water content (%) in air-dried condition [**] Asadi *et al.* (2018). [***] Abbas & Alhamdo (2023).

proceeding to apply it after mixing. (4) Applying fresh PC evenly and flattening it using a leveling machine to create a smooth surface. (5) Applying plastic mesh immediately after completing the surface. The surface layer was constructed with different gradations, and various types of PCs. Figure 3 illustrates this layout information.

Images of the monitored area are presented (Figs. 3 and 5) to compare surface temperatures in the monitored area. The surfaces in the study area had different base layers (Table 1) and different types of surface materials (Tables 2 and 3). These will affect surface temperatures when measured at the same time. Surface temperatures were determined based on thermal images captured across the entire area with the support of analytical software (Fig. 1). The amount of precipitation is essential information for evaluating the effectiveness of PC. The PC surface was watered for 30 minutes with a spray intensity of around 90 mm/h. Other situations included a 90-minute rainfall event with a total rainfall of 37.5 mm (rain intensity around 25 mm/h).

3. Results and Discussion

3.1 Compressive Strength and Permeability Coefficient

Testing of strength and permeability coefficient was conducted at two different times: immediately after construction and after nearly two years of use. Figure 4 shows core samples drilled from the PC and infiltration testing. The results are presented in Table 4. The compressive strength of the PC samples met the target, with strengths exceeding 7 MPa. In practice, this strength requirement has been met for use over the past two years. There was a decrease, however, in the strength of the samples that used RA, with a reduction rate ranging from 15% to 21%. In contrast, the regular concrete samples or PC samples using natural aggregate showed no significant difference in strength after two years (Table 4). The permeability coefficients of all surfaces were higher than the target of 4 mm/s. After two years, there was a reduction in the permeability coefficient, with the extent of reduction depending on the location and working conditions of each surface type. The permeability coefficient of the PC surfaces decreased on average by 4% to 9%. The PC1 surface, however, showed a significant average reduction in permeability, up to 53%. This can be explained by the fact that the PC1 surface directly received rainwater from the building's drainage pipes. The rainwater from the roof carried a lot of dust and visible mold, as observed with the naked eye. This phenomenon caused surface clogging and significantly reduced the permeability coefficient.

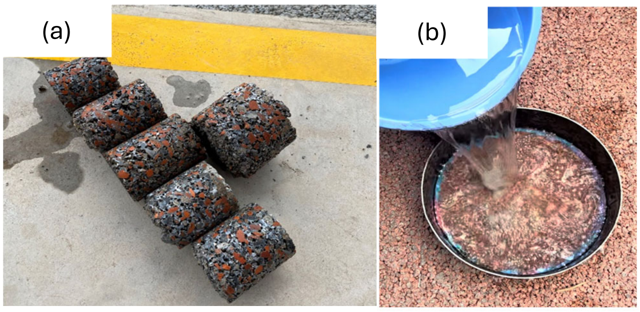

Fig. 4 (a) Core samples obtained by drilling for the compressive strength test from surface pavers. (b) Single ring infiltrometer test to measure water permeability of surface pavers.

3.2 Results of Testing the Effectiveness of PC in Surface Temperature Reduction

Surface temperature monitoring was conducted in the experimental parking area, which had an approximate area of 150 m^2, as shown in Fig. 2. The measurements were taken during the summer season under various conditions, including a day with sudden rain at 4:30 PM (natural rain), and a day with surface watering (simulated rain) from 9:00 AM to 9:30 AM. The results showed that water-retaining materials could retain up to 70% of their water absorption capacity for up to 30 minutes (Djerbi Tegguer, 2012), whereas typical rain events often last from 30 to 45 minutes or longer. Figure 5 shows thermal images and temperature ranges in different regions at two time points, 12:00 PM and 9:00 PM. The results demonstrate significant temperature variations between

Table 4 Water permeability and compressive strength of surface pavements in the initial stage after construction (Dec. 2021) and at the stage after 18 months (Jun. 2023).

Type		Water permeability (mm/s)		Δ %	Compressive strength (N/mm^2)		Δ %
		Dec. 2021	Jun. 2023		Dec. 2021	Jun. 2023	
PC1	Hanoi	5.3	2.5	53	11.0	8.9	19
(RCA 50% + NA 50%)	Hai Phong	5.4	4.3	13	11.6	11.1	11
PC2 (RCA 100%)		5.7	5.2	9	10.3	8.1	21
PC3 (RCA 90% + AAC 10%)		5.0	4.8	4	8.2	7.6	15
PC4 (RCA 90% + AAC 10%) – No base course		5.0	4.7	6	8.2	7.6	15
PC5 (NA 100%)		5.4	5	7	17.5	17.2	13
CC		–	–	–	26.7	26.4	1
ACR		–	0.3	–	–	–	–

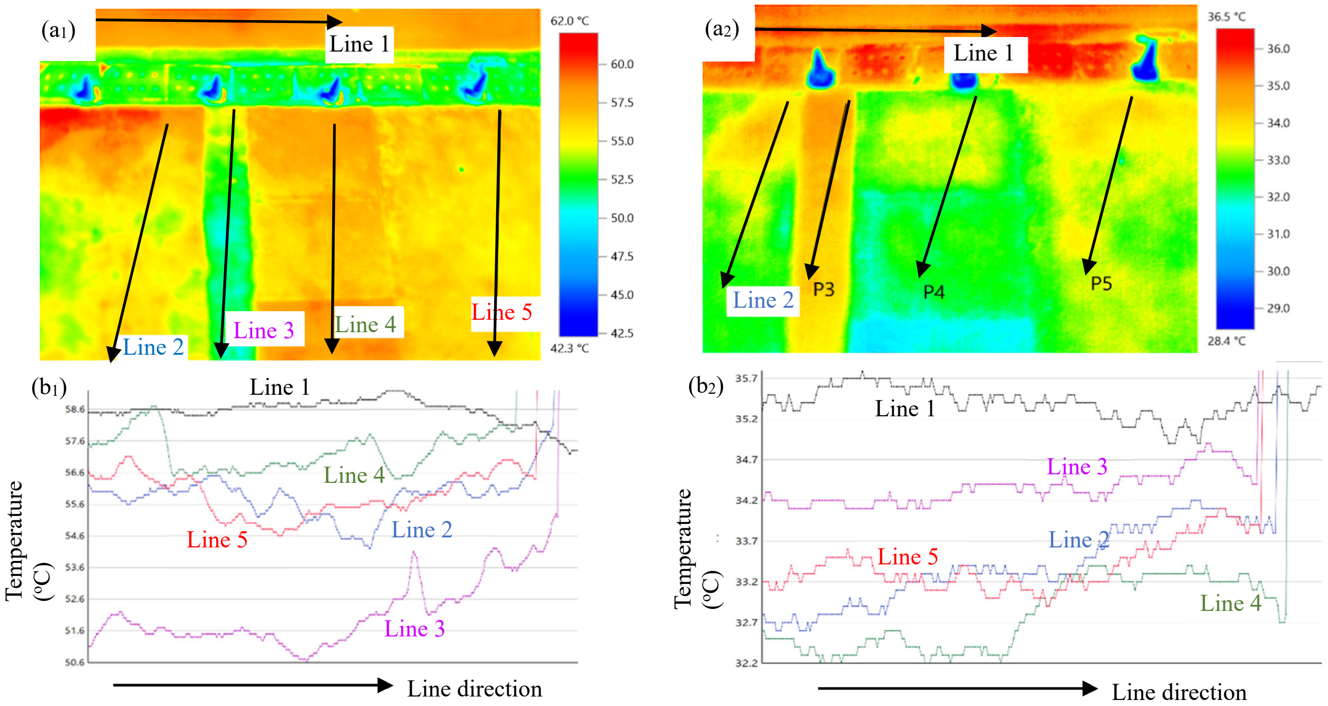

Fig. 5 (a_1) (a_2) Example of measured thermogram and (b_1) (b_2) temperature distribution along the lines measured at 12:00 (a_1) and 21:00 (a_2) on 13 June 2023.

different surfaces and at different times of the day. Two specific time points were chosen to assess the temperature: 12:00 PM (approximately the time of the highest outdoor temperature during the day) and 9:00 PM (approximately 4 hours after sunset). Figure 5 shows the temperatures at 12:00 PM and 9:00 PM with the average temperatures across the surfaces determined through the mean temperature on each thermal line (a collection of temperature measurement points), as shown in Tables 1, 2 and 3. The results indicate that the ARC surface had temperatures 1°C – 5°C higher than the PC surfaces and 4°C – 8.4°C higher than the conventional concrete (CC) surface.

At 9:00 PM, the asphalt (ACR) surface still had the highest temperature (P1 ≈ 35°C), while the PC surfaces had lower temperatures, with the average temperature along lines 2, 4 and 5 ranging from 32°C to 33°C. In contrast, the CC surface cooled down slowly and had only a slightly lower temperature than the ACR surface, with an average temperature along Line 3 of about 34.5°C. Therefore, after about four hours after sunset, the surface temperatures had decreased by more than 20°C compared to at noon. However, there were still temperature differences among the surfaces. The PC surfaces had temperatures 2°C – 3°C lower than the ACR surface and 1.5°C – 2.5°C lower than the CC surface. This difference can be explained by the larger surface area of PC, which leads to greater absorption of solar radiation. Therefore, at the hottest point of the day, the surface temperature of PC (lines 2, 4 and 5) can be equivalent to, or even higher than, the temperature of the ACR surface (Line 1). At noon (12:00 PM), CC has the lowest surface temperature (Line 3) due to its specific heat capacity of approximately 924 J/kg·K, which is higher than that of ARC (around 850 – 900 J/kg·K). For materials with larger pore structures like PC, their specific heat capacity tends to be lower, which means that the heat absorption and temperature increase of CC will be slower compared to those of other materials. Additionally, the CC surface is lighter in color compared to the other surfaces (red, gray-black), which results in lower heat absorption.

Figure 6a depicts the temperature correlations among the surfaces within the monitoring area throughout the daytime. Temperatures were recorded from 9:00 AM to 10:00 PM. Surface temperatures increased and reached their peak between 9:00 AM and 1:00 PM. During this time frame, the temperature increase rate for the PC surfaces (dashed lines) was equivalent to that of the ACR surface and significantly higher than that of the CC surface. At the time when the surface temperatures reached their maximum, there was a difference of approximately 5°C, with the CC surface having the lowest temperature. During the cooling process, the ACR and CC surface temperatures decreased more slowly than the PC surfaces. By 6:00 PM, all of the PC surfaces had lower temperatures than the ACR and CC surfaces, with the maximum temperature difference at that time being 6.1°C. From 6:00 PM to 10:00 PM, the surfaces continued to cool, maintaining a temperature difference ranging from 2°C to 3°C.

Figure 6b shows the surfaces' temperatures during the daytime when they were watered for 30 minutes between 9:00 AM and 9:30 AM. The 30-minute watering provided enough moisture to saturate the sublayers and the water-absorbing capacity within the structure of the PC, utilizing the water-retaining role of PC made with

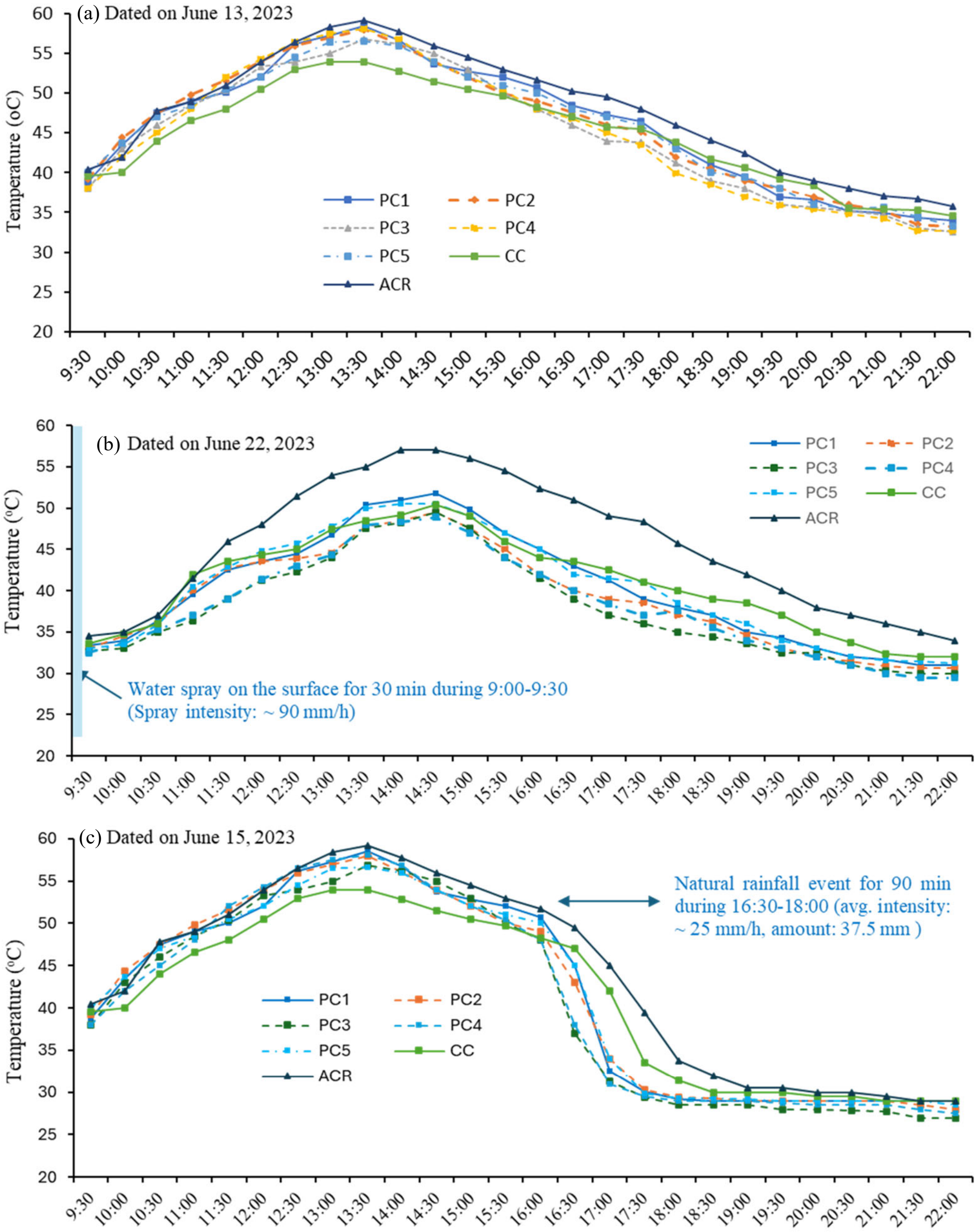

Fig. 6 Temporal changes in surface temperature for different types of surface pavers under three conditions at the Hanoi site: (a) daytime with no rainfall event, (b) daytime after water spray in the morning, and (c) daytime with a natural rainfall event.

AAC. The results reveal that two hours after the watering stopped, the surfaces heated up very slowly due to the lingering water. However, after two hours, the ACR and CC surfaces had dried, and the heating process began following a pattern similar to that in Fig. 5. The temperature correlations among the PC surfaces varied, with PC3 and PC4 surfaces showing the lowest temperature increase and the fastest decrease among the PC surfaces. The largest temperature difference, 8.1°C compared to the ACR surface, occurred at 2:30 PM, while the PC3 and PC4 surfaces had temperatures about 2°C – 3°C lower than the PC1, PC2, and PC5 surfaces. The research results in Fig. 6 (b) also demonstrate the effectiveness of water evaporation from the AAC in the PC2 and PC3 surfaces in reducing surface temperatures compared to the other PC surfaces. This increased the temperature difference with the ACR and CC surfaces by about 6°C – 12°C. At 10:00 PM, the PC2 and PC3 surfaces remained cooler than the others by 2°C – 6°C. Water has a significantly higher heat capacity than concrete materials (4200 J/kg·K). Using AAC increases the retained water content, thereby increasing the specific heat capacity of PC. Therefore, the PC2 and PC3 surfaces heated up more slowly but cooled down faster due to the evaporation process.

The next research results were obtained during a day with natural rain occurring at 4:00 PM (Fig. 6 (c)). The patterns of temperature increase and decrease between 9:00 AM and 4:00 PM were similar to those in Fig. 6 (b). When rain occurred at 4:00 PM, however, the temperatures of the surfaces varied to different extents during the rain and after the rain had stopped.

Just before the rain, the PC3, PC4, and CC surface temperatures were the same and at their lowest; the PC1, PC2, and PC5 surfaces had higher temperatures but those were all lower than the ACR surface temperature. During the rain, the temperatures of the PC surfaces decreased rapidly from around 48.3°C – 52°C to approximately 30°C – 31°C. Due to their porous structure, PC surfaces cool down quickly as the surface comes into contact with flowing rainwater. The PC3 and PC4 surfaces, with AAC, rapidly absorb water, resulting in the quickest and deepest temperature drop.

In contrast, the ACR and CC surfaces cooled down slowly, reaching temperatures of around 40°C and 33.5°C, respectively, immediately after the rain stopped. They continued to decrease in temperature over the next two hours before stabilizing at around 29°C at 10:00 PM. After the rain stopped, the PC surface temperatures were similar to the environmental temperature and gradually decreased to around 27.5°C by 10:00 PM.

4. Conclusions

In the daytime, the temperature increase process for the PC surfaces was similar to that of asphalt concrete, while the regular concrete heated up more slowly than the other surfaces. However, the temperature decreased faster for the PC surfaces than for the ACR and CC surfaces, resulting in an increasing temperature difference as the day progressed.

Watering the surfaces in the morning had no significant impact on the ACR and CC surfaces. After about two hours, the cooling effect of watering and water evaporation on the surface ended, and the surface temperatures followed the usual temperature increase pattern. For the PC surfaces with AAC in general, however, the surface temperatures increased but remained significantly lower than under sunny conditions. The process of water evaporation effectively reduced the temperatures of the PC surfaces, as was demonstrated by the surface temperatures of those using AAC.

During the sudden rainfall, the PC surfaces showed a rapid cooling to the environmental temperature due to the efficient heat exchange with a large amount of falling rainwater. In contrast, the ACR and CC surface temperatures showed a slower reduction and maintained higher temperatures than those of the PC surfaces after the rain had stopped.

These observations highlighted how the characteristics of different surface materials, particularly those with AAC, influence their temperature behavior under different weather conditions, including daytime, watering and rainfall.

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