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REVIEW OF WATER AND HEAT BALANCES AND CHALLENGES TO ADOPTION OF PERMEABLE PAVEMENT SYSTEM IN VIETNAM

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ABSTRACT: Permeable pavement system (PPS) contributes to mitigating urban floods and urban heat islands (UHI). PPS has been widely used in developed countries for low-traffic areas, parking lots, and sidewalks. However, PPS has not received much attention in developing countries such as Vietnam. Monitoring studies on PPS mostly focus on hydrological and thermal performance related to volume, rate of flow, and surface temperature, but studies of water and heat balances are somewhat limited. This study, therefore, summarizes hydrological and thermal performance especially focusing water and heat balance in PPS, and the measurement techniques/instruments to construct a suitable monitoring system for application to pavement. In addition, challenges to the adoption of PPS in Vietnam were also investigated, fully considering technical standards/requirements and case studies in developed countries. The results showed that PPS contributes to flooding control due to a large infiltration/drainage component. Water vapor carries away a portion of the energy that arrives at the pavement surface, resulting in a reduction in sensible heat and UHI. Evaporation has been the most difficult component to accurately quantify. A lysimeter system is commonly used to measure components of water balance but cannot be easily integrated into a full-scale PPS installation. A monitoring vault can be used in full-scale applications, but a suitable method is required to accurately determine evaporation. The challenges/requirements for PPS adoption in Vietnam include site-specific, technical/engineered, economic, environmentally friendly, associated facilities, current policies, and awareness.

Keywords: Permeable pavement system, Water and heat balance, Monitoring, Barriers and challenges

1. INTRODUCTION

The concept of PPS was proposed in the late 1960s to minimize flooding and increase groundwater levels [1]. In addition, cool pavements (e.g., PPS) have been identified by the United States Environmental Protection Agency as one strategy for mitigating urban heat islands (UHI), and promoted the installation of cool pavements [2]. There have been many studies on PPS, expanding from design, construction, and maintenance to performance for various types of PPS, such as permeable asphalt pavement (PAP), pervious concrete pavement (PCP), and permeable interlocking concrete pavement (PICP). Having a good track record in performance of noise reduction, flood reduction, groundwater pollution reduction, UHI reduction, and longevity compared to conventional pavement [1,3], PPS has been developed rapidly throughout developed countries such as the US, Canada, and Japan, despite some limitations such as the risk of groundwater contamination, cost, untested long-term performance, and clogging [4]. Some road associations in the US and Japan have issued guidelines on the design, construction, and maintenance of PPS [1,3,5-6]. However, limited understanding of the short- and long-term performance with respect to water and heat balance is perhaps partly due to the lack of a suitable monitoring system that can be used easily during construction and throughout the lifespan of PPS. Moreover, PPS has not received widespread attention in developing countries such as Vietnam. Till now, there is no published standard/guideline for PPS in Vietnam to the authors' best knowledge. In Vietnam, there have been limited studies on PPS, and mainly focusing on mechanical and hydraulic properties of surface layer [7-8]. This indicates that developers, designers, engineers, and planners are hesitant to implement this technology. In this study, therefore, studies on hydrological and thermal performance, with a special focus on water and heat balance, and the monitoring techniques/instruments to measure their components are summarized. In addition, the barriers/requirements for the adoption of PPS in Vietnam, considering the experiences of developed countries, and specific conditions in Vietnam have been synthesized. This review aims to establish a suitable monitoring system that can be used to evaluate the water and heat balance process, for both outdoor experiments and full-scale applications, and to promote the potential adoption of PPS in Vietnam.

Table 1 Definition of permeable pavement

Terms	Abbreviation	Definition	Ref.
Permeable pavement systems	PPS	A pavement system allows stormwater to filter through voids in the pavement surface into an underlying rock reservoir where it is temporarily stored and infiltrated into the surrounding materials	[5]
Porous asphalt pavement	PAP	Permeable pavements surfaced with asphalt concrete	[6]
Pervious concrete pavement	PCP	Permeable pavements surfaced with cast-in-place concrete	[6]
Permeable interlocking concrete pavement	PICP	Permeable pavements surfaced with interlocking concrete block pavers	[6]

2. RESEARCH SIGNIFICANCE

The concept of water and heat balance for PPS is important to satisfy effective functions required to design the system and to establish a suitable monitoring system. The monitoring system of PPS for investigating the water and heat balance would provide a tool for evaluating the performance and cost effectiveness, and operation/maintenance of PPS. The summary of barriers and challenges/requirements can also be expected to solve the mitigation of UHI and the control of urban flooding, especially in big cities in Vietnam.

3. METHODOLOGY

This review searched a database that includes publications mainly by the American Society of Civil and Engineers (ASCE), National Asphalt Pavement Association (NAPA), Japan Road Association (JRA), and Web of ScienceTM using several keywords, including permeable pavement system, permeable asphalt pavement, pervious concrete pavement, permeable interlocking concrete pavement, in combination with design, hydrologic, hydraulic, water quality performance, water and heat balance, monitoring, cost, barriers, and challenges. Based on this search, previously published research papers, reports, technical standards, and case studies published mainly after 2000 were selected for review. The abbreviations and definitions of permeable pavement used in this study are summarized in Table 1.

4. RESULTS AND DISCUSSION

4.1 Permeable pavement system

A permeable (also called porous or pervious) system allows water to infiltrate and be conveyed through its material matrix, open joints, or voids as defined in Table 1. The terms permeable, porous, and pervious are frequently used interchangeably. Most research has focused on commercially applied materials such as PAP, PCP, and PICP. Some basic hydraulic and thermal properties of the typical surface of PPS are summarized in Table 2. Poured PPS is designed with a high total porosity, ranging from 15–35%, while modular PPS often has a lower total porosity of about 5–15%, which is mainly contributed by the voids of the joints [1,6,9-11]. The high hydraulic conductivity of the newly constructed surface is commonly 0.10–0.62 cm/s [1,10,12-13], far exceeding the minimum surface hydraulic conductivity requirement of 6.94×10^{-3} cm/s (25 cm/h [6]). The higher air void ratio of poured PPS leads to lower thermal conductivity [14-18]. The lowest range of albedo of PAP is attributed to the black color of the asphalt binder [2,15,19-20].

Depending on the site-specific climate, traffic conditions, target concepts, and setting performance, PPS design varies greatly to meet both hydrologic and structural functions [3,5-6]. Where there is a high water table or risk of groundwater contamination, an impermeable geotextile can be considered [3,6,21]. Materials used for the base/subbase of PPS nowadays are shifting from natural materials to recycled materials because they have strength similar to natural materials and are environmentally friendly [22]. Construction, maintenance methods, and equipment requirements were thoroughly discussed in the guiding standards and previous review work [1,3-4, 6,9-10,23-24]. The maintenance of PPS is mainly related to identifying clogging by direct inspection, and then recommended optimal time intervals [3,9,25]. New methods to assess clogging dynamics in PPS, with time domain reflectometers (TDR) [26-27] for example, should be incorporated into the standard. Case studies and review work have repeatedly found that the removal by concentration or mass of suspended solids and heavy metals (e.g. Pb, Zn, Cu, and Cd) is reduced by at least 50% compared to impervious pavement due to the reduction in total outflow volume or by infiltration through PPS [28-31]. Safety and environmental benefits including improved wet pavement fractional resistance, reduced hydroplaning, reduced splash and spray, reduced night time glare, and reduced pavement noise have been confirmed [3,9-10,32]. However, without verifiable effective-life estimates and proven maintenance practices, the operational costs and true life-cycle cost of this technology remain unclear [4].

Table 2 Basic hydraulic and thermal properties of the typical surface layer of PPS

Type	Hydraulic properties			Thermal properties		
	DD (g/cm^3)	ϕ (%)	K_s (cm/s)	λ (W/m/K)	c_p (kJ/kg/K)	α
Permeable asphalt	1.9-2.4	16-25	0.10-0.40	0.82-1.16	0.92-2.00	0.07-0.10
Permeable concrete	1.7-2.1	15-35	0.14-1.22	0.47–0.81	0.84-1.05	0.18-0.42
Block	As per manufacturer	5-15	0.50-0.62	1.20-1.47	0.73-2.90	0.25-0.28
Ref.	[16-17]	[1,6,9-11]	[1,10,12-13]	[14-18]	[14-18]	[2,15,19-20]

DD: Dry density; ϕ: Total porosity; K_s: Saturated hydraulic conductivity; λ: Thermal conductivity; c_p: Specific heat capacity, α: Albedo

4.2 Hydrological performance

Research objectives of hydrological performance typically focus on quantifying the volume and peak flow reduction [29,33-35,37-38]. Table 3 summarizes the details of the pavement characteristics and methodologies adopted for evaluation of the hydrological performance.

4.2.1 Volume and peak flow reduction

In flood control, the hydrological performance with regards to outflow volume and peak flow reduction is important. Figs. 1a and b present the volume and peak flow reduction as a function of type of PPS.

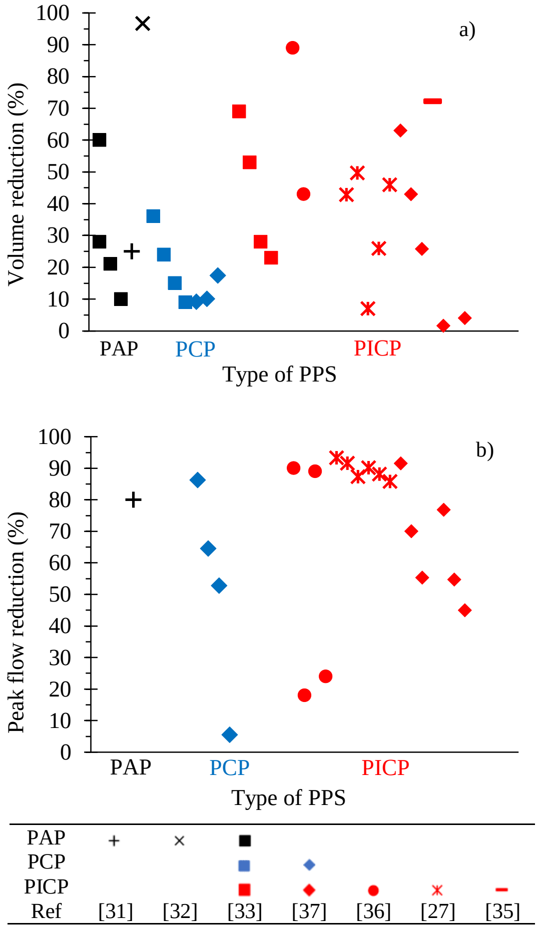

Fig. 1 The effect of type of PPS on a) volume reduction, b) peak flow reduction

It can be seen that the reported volume and peak flow reductions are less consistent between studies and highly variable within individual studies. As shown in Table 3, differences in location, geological conditions, and design (e.g., pavement structure configuration and soil subgrade permeability) might cause this variation. Therefore, when assessing the overall hydrologic performance, it is necessary to comprehensively consider all influencing factors.

4.2.2 Water balance concept

Water balance is a concept that is commonly used in hydrology. It can also be applied to urban areas [33,39-42]. The general equation describing the water balance in a pavement zone may be expressed as:

$$P = R + E + I + D + \Delta W \quad (1)$$

where the term on the left-hand side of Eq. (1) is precipitation P. On the right-hand side of Eq. (1), are the surface runoff R, the evaporation E, the infiltration I below the soil subgrade zone, the drainage D, and the water storage ΔW in the pavement profile. The components of water balance for different typical pavement types is shown in Fig. 2.

4.2.3 Water balance performance

Hydrologists are interested in what fraction of the incoming water (i.e., precipitation) will result in the direct runoff and deep infiltration to the soil subgrade below, while meteorologists might need to know about evapotranspiration. Designers need to know all components in the water balance equation to design a suitable PPS. The most signification output of PPS is the infiltration and/or drainage components, while the lowest output is the runoff [33,39-44]. Two conventional asphalt pavements from different studies behaved similarly, with the greatest fraction from precipitation appearing as runoff, while the fraction lost by evaporation also accounted for a fairly large proportion (i.e., about 20% [43-44]). However, the amount of evaporation from conventional pavement is mainly attributed to fast-drying surfaces, while that of PPS shows more evenly distributed evaporation after a rain event [45].

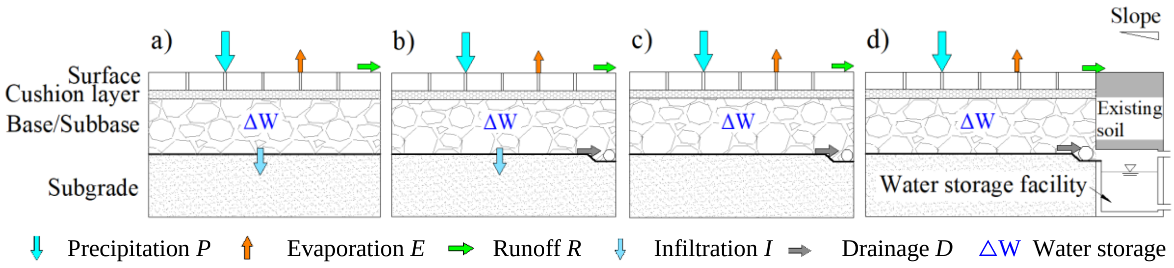

Fig. 2 Typical structure and components of water balance (modified after [3,6,39-41]) for a) full infiltration, b) partial infiltration, c) no infiltration, and d) no infiltration with a water storage facility

The relative values of the drainage and/or infiltration component of 38–75% for PPS are much greater than that of the only 8% for conventional pavement [33,39-44]. It is noted that compared with studies on quantifying the volume and peak reduction, studies on measuring water balance are very limited (Table 3). Furthermore, the water storage component is often ignored [33,39-44]. Recently, however, studies have not only focused on traditional materials, but water-retaining materials have also been developed [22,46]. Therefore, water storage is likely to account for a large proportion of the water balance, especially during a rainfall event.

4.3 Thermal performance

Research objectives on thermal performance typically focus on examining the surface temperature [2,15,19-20,48]. Table 4 summarizes the pavement characteristics and methodologies adopted for the evaluation of thermal performance.

4.3.1 Surface temperature

The surface temperature performance of PPS varies depending on thermophysical properties and available moisture in and near the surface pavement [2]. Surface temperatures generally decrease as thermal conductivity, specific heat capacity, and albedo increase [2,20,48]. Surface temperatures of PPS can be higher than that of conventional pavements in dry conditions [2,20]; however, Li et al. [2] examined the effect of water on the surface temperature and found that the surface temperature of PCP was lower than conventional concrete pavement up to about 2 days after watering. This indicated the importance of the water storage component in water balance. Under the same weather conditions, PAP pavement often exhibited a higher surface temperature than PCP and PICP pavement. This is probably due to the strong effect of a low albedo on the surface temperature (Table 2).

4.3.2 Heat balance concept

PPS was used originally for the drainage of urban streets. However, since they allow the exchange of water between the atmosphere and the pavement, evaporation can occur at the surface. Due to evaporation, a part of the net downward radiation is converted into latent heat, similar to the phenomena happening at natural surfaces covered by bare soil or vegetation [14]. The heat flux balance concept that often used for soil or crop canopy surface [49-51]; however, it can also be used for the pavement surface [14,19], and can be expressed as:

$$R_n = LE + S + G \tag{2}$$

where the term on the left-hand side of Eq. (2) is the net radiation R_n that arrives at the pavement surface. On the right-hand side of Eq. (2) is the latent heat flux *LE*, which represents the water vapor flux into the atmosphere by evaporation, the sensible heat flux *S*, which represents the vertical transport of warm air from the surface zone to the atmosphere above, and the ground heat flux *G*, which represents the vertical transport of heat into the pavement. Typical components of the pavement surface heat flux balance for day and night time are illustrated in Fig. 3a and b.

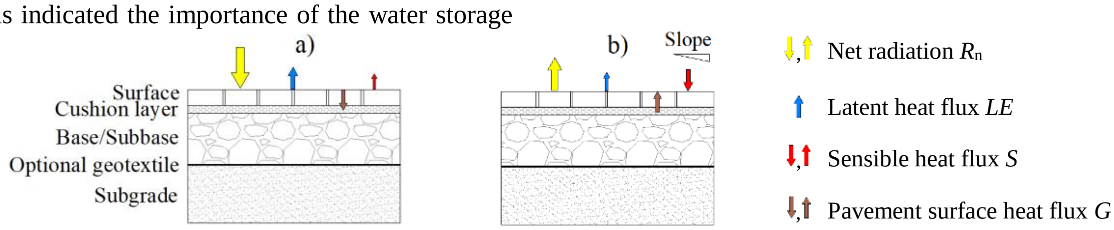

Fig. 3 Typical components of the surface heat flux balance (modified after [14,19] for a) daytime, and b) nighttime

4.3.3 Heat balance performance

Studies evaluating the effect of PPS on UHI are mainly based on the assessment of the surface temperature of PPS as compared with that of conventional pavement (Table 4). Studies on the heat budget of PPS are very limited [14,19]. A large portion of the energy from the sun that arrives at the pavement surface was converted to latent heat. A range of 16–52% accounted for latent heat flux through evaporation [14,19]. This results in less transfer of sensible heat from the pavement surface into the near atmosphere and ground heat into the pavement. In contrast, because conventional pavements limit evaporation from the underlying material, most of the solar radiation is converted to sensible heat and ground heat in the pavement. The sensible heat flux and ground heat flux were in the range of only 28–54% and 24–33%, respectively, for PPS while that of conventional asphalt was 56–61% and 39–42% [14,19]. There was almost no latent heat flux from conventional asphalt [14,19]. Many parameters affect the surface heat budget such as albedo, evaporative efficiency, heat conductivity, and heat capacity [19].

4.4 Monitoring

4.4.1 Water balance monitoring system

The water balance concept has been applied to urban areas, but the complexity of the urban water cycle can make its application on a catchment scale more difficult [42]. On a smaller scale such as PPS in sidewalk and parking lots, the difference between precipitation and runoff for paved surfaces is largely accounted for by losses due to surface wetting and water storage as well as infiltration and drainage [42]. In such cases, storage would include water that is held in the pavement surface and base/subbase profile. Moreover, as previously discussed on water balance performance, evaporation from PPS accounts for a rather large portion of total incoming water. Hydrologists, meteorologists, and designers need to know the performance of each component for both short- and long-term. The schematic of a monitoring system for quantifying water balance components from previous studies is shown in Fig. 4.

The water balance components are often defined using a weighable lysimeter [40-41] or a monitoring vault system [33,39]. A lysimeter is a vessel container with local soil placed with its top flush with the ground surface for the study of several phases of the hydrological cycle [41]. The lysimeter surface can be free, planted, or paved. A lysimeter measures the change of the lysimeter body weight, along with mass measurement of water runoff, infiltration, and drainage [41,47]. The runoff is often measured using a tipping bucket, while the infiltration and drainage can be measured using a high-resolution scale system [41,47].

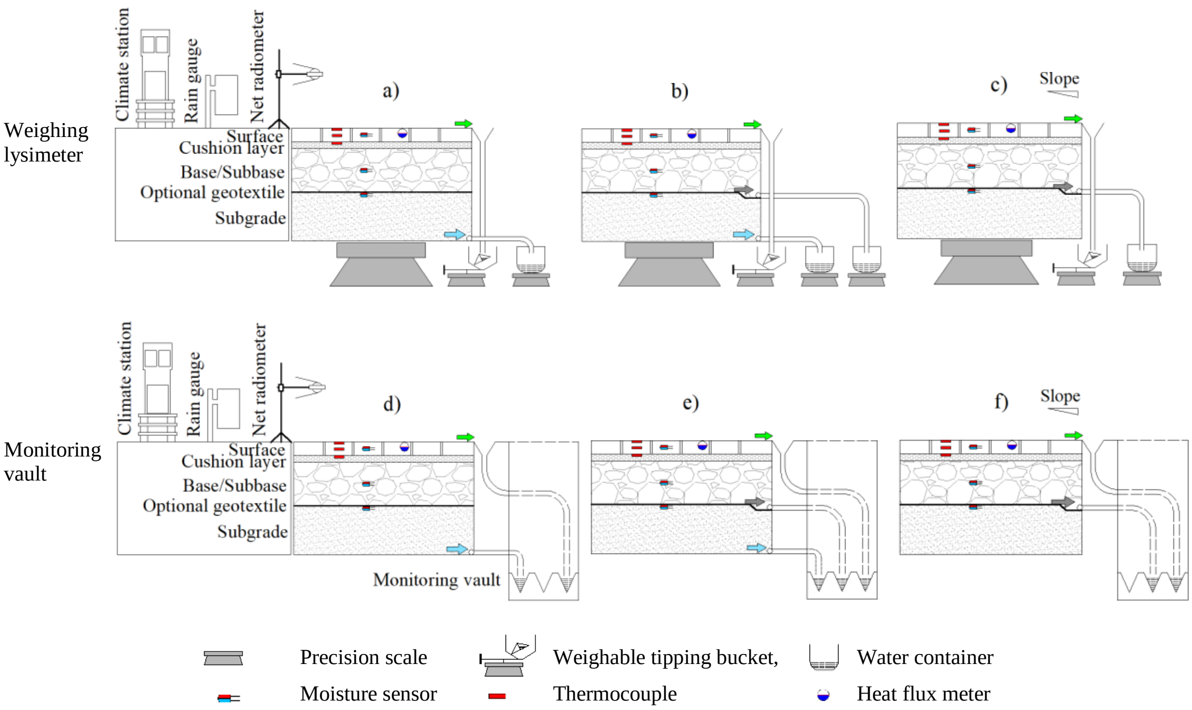

Fig. 4 Schematic of a monitoring system for measuring water (modified after [33,39-41,47]) and heat (modified after [14,19]) balance components using weighing lysimeter and monitoring vault system for a, d) full infiltration; b, e) partial infiltration, and c, f) no infiltration type

Table 3 Summary of pavement characteristics and methodologies adopted for evaluation of the hydrological performance

Type	Location	Application	Pavement characteristic	Drain configuration	Apparatus/Methodology	Items to be quantified	Ref.
PAP	New Hampshire, USA	Parking lot	Surface 10 cm with ϕ= 18 %, base/subbase includes choker course 10 cm, poorly graded gravel 61 cm, and crushed stone 10 cm	Type C soil, K_s=6.94×10^{-5} (cm/s), geotextile, underdrain	Rainfall and runoff were measured by a rain gauge and a Thel-Mar weir	Volume and peak flow reduction$^{*)}$ Water balance	[33]
PAP	Reze, France	Parking lot and sidewalk	Surface 6 cm, base/subbase includes crushed material 35 cm and porous bituminous bound graded aggregate 20 cm	Geotextile	N/A	Volume reduction	[34]
PAP	City of St. Louis, USA	Pilot study	Surface 5-10 cm with ϕ=16 %, no base/subbase	Silty clay loam	Rainfall and runoff were measured by rain gauge and flow meter	Volume reduction	[35]
PAP	Nantes, France	Laboratory	Surface ϕ= 18%, no base/subbase	No	Weighable lysimeter.	Water balance	[40]
PCP	City of St. Louis, USA	Pilot study	Surface 10-30.5 cm with ϕ= 15-25 %, no base/subbase	Silty clay loam	Rainfall and runoff were measured by rain gauge and flow meter	Volume reduction	[35]
PCP	North Carolina, USA	Parking lot	Surface 15 cm, base/subbase includes No. 78 stone 5 cm and No. 5 stone 23 cm	Sandy loam to sandy clay loam, underdrain	Rainfall and runoff were measured by tipping bucket rain gauge and 30° V-notch weir	Volume and peak flow reduction Water balance	[39]
PICP	City of St. Louis, USA	Pilot study	Surface brick paver with joints of 2-5mm, no base/subbase	Silty clay loam	Rainfall and runoff were measured rain by gauge and flow meter	Volume reduction	[35]
PICP	North Carolina, USA	Parking lot	Surface 8 cm with ϕ= 8.5-12.9%, base/subbase includes No. 78 stone 10 cm and No. 5 stone 25 cm	Sandy loam to sandy clay loam, underdrain	Rainfall and runoff were measured by tipping bucket rain gauge and 30° V-notch weir	Volume and peak flow reduction Water balance	[39]
PICP	Auckland, New Zealand	Driveway	Interlocking block surface, base/subbase 38 cm	Silty clay and clayey silt, K_s= 1.16×10^{-6} (cm/s), underdrain	Rainfall and runoff were measured by tipping bucket rain gauge and 120° V-notch weir	Volume and peak flow reduction	[29]
PICP	Connecticut, USA	Driveway	Interlocking block surface, base/subbase includes compacted coarse 5 cm and processed gravel 15 cm	Fine sandy loam	Rainfall and outflow were measured by tipping buckets.	Volume reduction	[37]
PICP	Ohio, USA	Parking lot	Surface 8 cm, base/subbase includes No. 8 stone 2.5-3.8 cm, No. 57 stone 15 cm, and No. 2 stone 40 cm	Silt loam, K_s= 9.17×10^{-5} (cm/s), underdrain	Rainfall and runoff were measured by tipping bucket rain gauge and 60° V-notch weir	Volume and peak flow reduction	[38]
PICP	Berlin, Germany	Field experiment	Large concrete pavers surface, base/subbase includes 0-2mm construction sand 130 cm, 2-4 mm gravel 20 cm	No	Weighable lysimeter (1.1×1.5 m)	Water balance	[41]
Conventional asphalt	Nantes, France	Laboratory	Surface 8 cm with ϕ= 5% , no base/subbase	No	Weighable lysimeter.	Water balance	[40]

Peak flow reduction, compared to the peak flow of outflow of PPS and peak flow of surface runoff of conventional asphalt pavement; volume reduction, compared to the volume leaving underdrain and surface runoff of PPS and conventional asphalt pavement, unless noted

$^{*)}$ Compared to calculated rainfall volume, K_s: See Table 2, N/A: not available

Table 4 Summary of pavement characteristics and methodologies adopted for evaluation of surface thermal performance

Type	Location	Laboratory/ Field experiment	Pavement characteristic	Weather condition	Apparatus/Methodology	Items to be quantified	Ref.
PAP	N/A	Laboratory and field experiment	Laboratory experiment: Cylindrical samples of 15×15 cm with ϕ= 18% were used to determine λ and c_p Field experiment: Slab samples of 50×40×7.5 cm with ϕ= 18% were used to determine T_{sur}	T_{air}: 21-34 ºC	c_p, λ, and α were measured following ASTM C341-92b, ASTM C177-04, and ASTM E1918, respectively. T_{sur} was recorded using a temperature gun	α, λ, c_p, T_{sur}	[48]
PAP	California, USA	Field experiment	Area of 4×4 m, surface 10-20 cm, base/subbase 30 cm	Peak solar radiation 1000 W/m^2, T_{air} 10-36 ºC, wind speed < 1m/s	α was measured following ASTM E1918 T_{sur} was recorded by thermocouple	α, T_{sur} α, T_{sur}	[2,20]
PCP	California, USA	Field experiment	Area of 4×4 m, surface 10-20 cm, base/subbase 30 cm	Same as above	Same as above	Same as above	[2,20]
PAP PCP	Osaka, Japan	Field experiment	Area of 2×2 m, surface 5 cm with ϕ= 13.6 %, base/subbase includes improved board 170 cm and filter sand 10 cm	Peak solar radiation 900 W/m^2, T_{air} 26-37 ºC, wind speed < 3.5 m/s, RH 30-90%	Temperature was recorded by thermocouple. G and R_n was observed by conduction heat flow meter and net radiation meter	Surface heat flux balance	[19]
PCP	N/A	Laboratory and field experiment	Laboratory experiment: Cylindrical samples of 15×15 cm with ϕ= 20% were used to determine λ and c_p Field experiment: Slab samples of 50×40×7.5 cm with ϕ= 20% were used to determine T_{sur}	T_{air} 21-34 ºC	c_p, λ, and α were measured following ASTM C341-92b, ASTM C177-04, and ASTM E1918, respectively. T_{sur} was recorded using temperature gun	α, λ, c_p, T_{sur}	[48]
PCP	N/A	Field experiment	Area of 0.3×0.3 m, surface layer 15 cm with ϕ= 15.1-24.9%, base/subbase 15 cm	Peak solar radiation 979 W/m^2, T_{air} 27-39 ºC	λ was measured using computer-controlled uni-axial heat flow meter, c_p was calculated from the c_p of each material. T_{sur} was recorded by thermal resistance temperature sensor	α, λ, c_p, T_{sur}	[15]
PICP	California, USA	Field experiment	Area of 4×4 m, surface 10 cm, base/subbase 15-30 cm	Peak solar radiation 1000 W/m^2, T_{air} 10-36 ºC, wind speed < 1 m/s	α was measured following ASTM E1918 T_{sur} was recorded by thermocouple	α, T_{sur}	[2,20]
PICP	Osaka, Japan	Field experiment	Area of 2 x 2 m, surface 5 cm, base/subbase includes improved sand base 10 cm, board 10 cm, and filter sand 10 cm	Peak solar radiation 900 W/m^2, T_{air} 26-37 ºC, wind speed < 3.5 m/s, RH 30-90%	Temperature was recorded by thermocouple, G and R_n was observed by conduction heat flow meter and net radiation meter	Surface heat flux balance	[19]
PICP	Saitama, Japan	Field experiment	Area of 2 x 2 m, surface 30×30×6 cm with ϕ= 30%, base/subbase 15 cm	T_{air} 26-36 ºC, wind speed < 4 m/s, RH 46-98%	Temperature was recorded by thermocouple, G and R_n was observed by conduction heat flow meter and net radiation meter	Surface heat flux balance	[14]
Conventional asphalt	Same as above	Same as above	Area of 2 x 2 m, surface 5 cm, base/subbase 15 cm	Same as above	Same as above	Same as above	[14]

ϕ, λ, c_p, α: See Table 2, T_{sur}: Surface temperature, T_{air}: Air temperature, RH: Relative humidity, R_n and G: See Fig. 3, N/A: Not available

The disadvantage of a tipping bucket is the undefinable temporal resolution and the fact that small events can get lost without being included in sample groups if the runoff water is less than one tipping volume [41]. To handle this problem, a weighable tipping bucket is used as shown in Fig. 4. The water storage in the pavement profile is determined by the change of the lysimeter body itself. The precipitation P is determined using the rain gauge. This precipitation P can also be determined by the change in the total mass of the lysimeter body itself and outflow (runoff, infiltration, and drainage) [41]. The evaporation component will be estimated using the water balance equation. Monitoring vaults have been used to assess water balance on a volume basis [33,39]. Rainfall measurements are often measured using a rain gauge [33,39]. The drainage and runoff volume are monitored using a V-notch weir [33,39]. In the field of PPS, Collins et al. [39] and Roseen et al. [33] have used this monitoring system to assess the water balance of a full-scale parking lot. However, the evaporation and water storage components are often estimated as a residual using the water balance equation and are not measured separately. To evaluate the water balance process, an appropriate method to measure the evaporation and/or storage component is essential.

4.4.2 Heat balance monitoring system

The quantities observed are often the surface and inner temperature, the conduction heat flux into the pavement, and weather conditions such as air temperature, relative humidity, net radiation, precipitation, and wind direction and velocity. The schematic of a monitoring system for measuring the heat flux balance component is shown in Fig. 4. The net radiation is often measured with a net radiometer. The surface and inner temperature are measured using a thermocouple. The heat flux meter is often located just below the pavement surface. Other weather conditions are also measured by the weather station located next to the pavement site (Fig. 4). Evaporation is not only a component of the water balance but also of the energy balance. One of the most difficult tests, perhaps, is determining the latent heat flux component. Knowing the evaporation efficiency is often required to determine the latent heat flux. Several methods have been used to estimate the evaporation efficiency such as comparing drilled core weights directly from the pavement [14,19] or using TDR [52].

4.5 Potential adoption of PPS in Vietnam

4.5.1 Barriers and challenges/requirements for the adoption of PPS in Vietnam

The evolution of urban stormwater management has been shifting from conventional end-of-pipe treatment to contemporary sustainable drainage systems such as infiltration technology [21,53]. Innovative technology must demonstrate its compatibility with current values and norms of society to increase or guarantee its adoption rate [51]. Table 5 presents the barriers and challenges/requirements for the adoption of PPS in Vietnam.

The experience of developed countries showed that PPS still has limitations, such as its applicability under unfavorable conditions (i.e., poorly draining soil and a high water table), the potential risks of contaminating groundwater, and untested long-term hydrological function (i.e., greater than 2.5 years [4]). A suitable monitoring system to assess clogging has not yet been established. Besides, the construction of PPS often requires highly qualified human resources [5,9]. The initial cost might be higher than that of conventional pavement mainly due to the thicker layers of base/subbase [1,54]. Although designed to have the same lifespan as conventional pavement, PPS is generally expected to have a shorter lifespan [21]. All the above technical and environmental barriers need to be overcome. Due to the different climatic and site-specific conditions, establishing appropriate design guidelines is required to obtain a proper design under disadvantageous conditions such as low permeability of soil subgrade or extreme rainfall [9,55-56]. Monrose et al. [55] examined the challenges for the adoption of PPS in Small Island Developing States and stated that the locally suitable and available construction materials that can be used for PPS are a challenge/requirement that needs to be overcome. Ease of construction and maintenance is required to construct and maintain a simple PPS with local human resources [6-9]. A challenge/requirement to reduce the cost is promoting the use of locally friendly available materials because the increase in the initial price of PPS compared to traditional pavement mainly comes from the higher cost of the base/subbase [54-55]. Loss of hydraulic function is a major cause of reduced pavement life, requiring the establishment of a suitable clogging monitoring system [26-27]. However, even if technical and environmental barriers are addressed, PPS may not be widely developed or accepted as a new technology if there is no policy promoting the use of PPS and the social awareness of policymakers and citizens [1,6,55,57-59]. In the U.S., the concept of porous pavement was proposed in the 1960s, and since the 1970s many porous asphalt pavements have been constructed across the U.S. [1]. This demonstrates that if there is a policy to promote the use of PPS and the benefits of PPS are recognized by decision-makers and individuals, PPS stands a good chance of being accepted.

Table 5 Barriers and challenges/requirements for the adoption of PPS in Vietnam

No	Item	Barriers	Challenges/requirements	Ref.
1	Site specific	Poorly draining soil, high water table and extreme climate	Establish a suitable design guideline	[3,9,55-56]
		Groundwater contamination	Infiltration stormwater should subsequently be discharged into a suitable drainage system.	[6]
2	Technical/ Engineered	Clogging/ maintenance	Establish an applicable and suitable monitoring system to assess clogging	[26-27]
		Ease of construction, maintenance	Proposed a that system is simple to construct and maintain with locally available human resources and expertise	[6,9]
3	Sustainable	Durable	Perform lifespan as traditional pavement	[9]
4	Economical	Less investment	Reduce initial cost by use of available construction materials. Local construction materials are easily available	[54-55]
5	Environmentally friendly	Use of safe PPS	PPS and its construction materials used do not harm the environment	[3,22]
6	Associated facilities	Asynchronous	Compatibility with existing developments that do not use PPS practices	[64]
7	Policy	Policy on flood and groundwater control	Promulgating policies to encourage the use of PPS	[1,54-55,59]
8	Social	Awareness	Policymakers and individuals easily recognize PPS practice as being beneficial	[53,55,58]

4.5.2 Specific factors to be considered in Vietnam

Vietnam is classified as a region physically vulnerable to climate extremes and potentially to changes in the typhoon regime, high water table, and sea-level rise. Compared with the average annual rainfall from some areas in developed countries where PPS was constructed, such as New Hampshire, U.S.A. (1200 mm), and Auckland, New Zealand (1000 mm), the annual average precipitation of Vietnam is much higher with an average of 2050 mm in the rainy season and 1600 mm in summer [60-61]. Many areas in the Mekong Delta are under sea level with a mean elevation of only 80 cm above sea level [62]. The difference in climate and the high-water table needs to be carefully considered. Vietnam's current urban flood adaptation policies focus on the pipe network and living with floods [63]. The fact that associated facilities are designed to collect only surface water is also something to keep in mind when designing PPS (e.g., partial and no infiltration type) [64]. Potentially available materials such as recycled waste materials that can be used for the base/subbase of pavement in Vietnam [65] can be considered as a plus to promote PPS adoption.

5. CONCLUSIONS

PPS has been widely applied in parking lots and sidewalks. PPS have been used in some roadways. Design concepts, construction, and maintenance have been thoroughly discussed in previous work reviews and integrated into standards in developed countries. Hydrological performance studies show that PPS contributes to volume and peak flow reduction compared to conventional pavements. The hydrological performance is less consistent between studies and varies within individual studies depending on local climatic, geological conditions, and design. Thermal performance studies show that PPS has the potential to contribute to UHI under various moisture conditions. The surface temperature of PPS is strongly affected by thermophysical properties and moisture in and near the surface layer.

There are few studies on the water and heat balance of PPS. A large portion of the water from precipitation evaporates or infiltrates below, resulting in less rainwater becoming runoff. The evaporation process carries away a large portion of the energy that arrives at the pavement surface resulting in a reduction in sensible heat and UHI. The lysimeter system is commonly used to measure components of water balance but cannot easily be applied in full-scale PPS installation. The monitoring vault can be utilized in full-scale applications but needs a suitable method to accurately determine the evaporation. Concerning the heat balance, the most difficult component to estimate is latent heat.

The barriers and challenges/requirements for PPS adoption in Vietnam include the site-specific, technical/engineered, economic, environment, existing associated facilities, policies, and social awareness.

Further research is needed on the water balance, especially the water balance process and the role of water storage occurring during rainfall events. The role of water storage in the evaporation transport process also needs more investigation. In addition, carbon balance is a promising topic.

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