

Review

Cooling and Hydrological Performance of Porous Asphalt Pavements: A State-of-the-Art Review for Urban Climate Resilience

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Abstract

Urban districts are increasingly exposed to overlapping heat stress and stormwater loads driven by warming trends, more intense rainfall, and continued growth of impervious surfaces. Pavements occupy a large share of the public right-of-way, so their material and structural design offers a scalable pathway for urban climate adaptation. Yet the literature on porous asphalt remains fragmented, with hydrological performance often assessed using infiltration or permeability metrics in isolation, while thermal studies frequently report surface cooling without consistently tracking the governing water budget or its persistence. To reconcile these disconnected strands, this review synthesizes a conceptual hydro-thermal balance framework in which runoff mitigation and heat moderation are treated as a coupled problem controlled by storage, drainage pathways, and evaporative demand. Within this framing, cooling is primarily water-limited: permeability enables wetting and redistribution, but the magnitude and duration of temperature reduction depend on how much water is retained near the surface and how long it remains available for evaporation, rather than on permeability alone. The review integrates the current understanding of mixture structure and pore connectivity, permeability–storage behavior, moisture availability and evaporation, and the operational factors that govern performance persistence. Laboratory and field evaluation approaches are summarized alongside modeling methods used to interpret coupled hydro-thermal responses under different climates. Practical constraints—including clogging, maintenance requirements, and durability risks under repeated moisture–temperature cycling—are discussed as mechanisms that can progressively suppress both infiltration and water availability, undermining long-term function without performance-based specifications and life-cycle planning. Finally, design and policy implications are outlined for integrating porous asphalt into coordinated heat-and-stormwater strategies, and research priorities are identified to advance standardization, long-term monitoring, and coupled hydro-thermal–mechanical assessment.



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Keywords: porous asphalt pavement; evaporative cooling; urban heat island mitigation; stormwater management; hydro-thermal performance; urban climate resilience

1. Introduction

Urban areas are increasingly confronted with two interrelated pressures: elevated urban temperatures and intensified rainfall runoff associated with extensive impervious surfaces [1]. Spatial analyses indicate that heat stress and stormwater burdens frequently coincide at the neighborhood scale [2]. In Berlin, an assessment of more than 14,000 building and street sections identified 2270 sections simultaneously experiencing high urban-heat-island (UHI) conditions and elevated stormwater pollution loads. Approximately 93% of high-UHI areas overlapped with zones of increased runoff-related pollution, while about 38% of high-pollution areas were located within high-UHI zones [2]. These findings underscore that the UHI effect represents not only a concern for urban comfort and public health, but also a measurable energy burden. Evidence from Athens, as cited in this review, demonstrates substantial increases in cooling demand, peak electricity consumption, and overall urban energy use under intensified heat-island conditions [3]. Collectively, these interacting pressures reinforce the need for mitigation strategies capable of addressing heat accumulation and runoff generation through integrated urban infrastructure approaches [1,3,4].

Pavements represent a critical intervention point because they occupy a substantial proportion of urban land and directly influence both thermal exchange processes and stormwater dynamics [4,5]. From a climate-resilience perspective, rising air temperatures and increasing precipitation intensity necessitate pavement strategies that integrate materials selection, structural design, maintenance practices, and performance monitoring, rather than treating thermal and hydrological functions as independent objectives [6]. Surface structure plays a key role in near-surface thermal behavior. For example, open-graded asphalt has been shown to cool more rapidly during nighttime conditions under wind exposure compared with dense-graded asphalt, primarily because its interconnected pore structure enhances convective heat exchange [5]. Within this context, porous and evaporative asphalt pavement systems have gained increasing attention as multifunctional infrastructure solutions capable of combining stormwater infiltration capacity with surface cooling potential when moisture is available near the pavement surface [4,7].

Importantly, thermal benefits are not guaranteed by permeability alone, because cooling persistence ultimately depends on near-surface water availability rather than permeability alone [7,8]. Existing asphalt-focused syntheses indicate that evaporation-driven cooling is most effective when moisture remains within the upper surface zone, whereas rapid drainage can shorten the duration of cooling even in highly permeable systems. Nevertheless, meaningful temperature reductions have still been reported under very hot climatic conditions, highlighting the context-dependent nature of thermal performance [7,8]. More broadly, stormwater-oriented interventions such as green roofs and integrated urban water management portfolios that include permeable pavements demonstrate that improved water management can simultaneously deliver thermal benefits and broader societal co-benefits [9,10].

1.1. Objective and Scope

Despite the extensive body of research conducted separately on permeable pavements and cool pavement technologies, no unified synthesis has yet quantitatively linked pore-network structure, hydraulic storage dynamics, and evaporative cooling persistence within a single performance-based framework. Accordingly, this review conceptualizes porous asphalt (PA) as a coupled hydro-thermal system and synthesizes how design variables, water storage and transport processes, evaluation methods, and climatic or operational conditions collectively govern both runoff mitigation and cooling performance.

To address this gap, the present review is guided by the following objectives:

- Develop an integrated hydro-thermal framework that conceptualizes runoff control and heat mitigation as coupled system outcomes governed by water availability, storage behavior, and transport processes.
- Synthesize quantitative relationships that connect pore-network structure, including architecture and connectivity, with hydraulic storage and retention dynamics, as well as with the magnitude and persistence of evaporation-driven cooling.
- Compare laboratory experimentation, field monitoring, and numerical modeling approaches, with particular attention to the performance metrics required for cross-study comparability and to the limitations associated with interpretations based solely on permeability indicators.
- Identify design-relevant thresholds and performance trade-offs among infiltration capacity, near-surface moisture availability, drainage pathways, and structural requirements, thereby supporting the optimization of PA systems under defined climatic and operational boundary conditions.

Figure 1 presents the integrated conceptual synthesis framework adopted in this review, illustrating the relationships among the material and structural characteristics, governing hydrological and thermal mechanisms, PA system configurations, operational constraints, and resulting performance outcomes. The framework organizes the reviewed literature into interconnected components and explicitly emphasizes the coupled nature of hydro-thermal processes within porous pavement systems. By linking design variables to system behavior and measurable performance indicators, the figure provides a structured representation of the interactions and dependencies that define system functionality and long-term effectiveness under varying environmental and operational conditions.

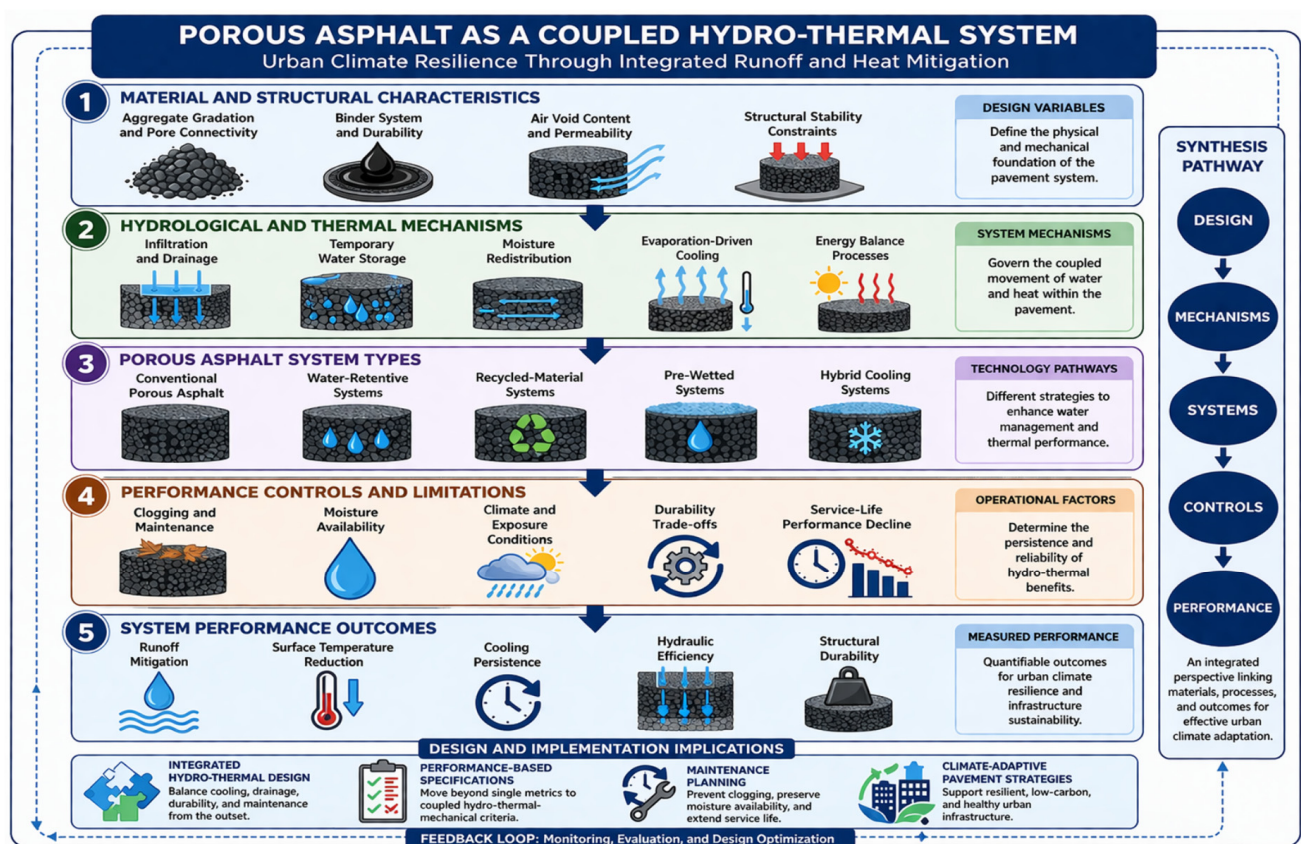


Figure 1. Conceptual organization of the literature review and synthesis pathway for PA system performance.

1.2. Literature Search Strategy and Review Scope

This review was developed as a narrative state-of-the-art synthesis rather than a formal systematic review. The reference base was compiled primarily from major scientific databases, including ScienceDirect and Google Scholar, using combinations of keywords related to PA pavement, evaporative cooling, UHI mitigation, stormwater management, hydro-thermal performance, and urban climate resilience. The literature coverage spans the period from 2001 to 2026, with greater emphasis placed on studies published after 2012 in order to reflect recent advancements in porous pavement technology, system design, and performance evaluation methods. Sources were selected based on their direct relevance to PA materials and structural characteristics, hydrological behavior, cooling mechanisms, evaluation approaches, climatic influences, and long-term performance trade-offs. The review relied predominantly on peer-reviewed journal publications, while also incorporating selected review articles and a limited number of additional sources, including thesis-level and conference-based publications, when they provided relevant and topic-specific evidence. This selection strategy enabled a focused synthesis of the most pertinent research while maintaining alignment with the stated objectives and scope of the review.

Several methodological limitations associated with the adopted narrative review approach should be acknowledged. Because the literature search was conducted using a defined set of databases and keyword combinations, some relevant studies indexed in alternative databases or reported in less accessible sources may not have been captured. In addition, no formal risk-of-bias assessment or quantitative meta-analysis was performed, as the purpose of this study was to provide an integrated qualitative synthesis of current knowledge rather than a statistically pooled evaluation of results. Moreover, the available evidence base in this field remains relatively specialized and context-dependent, particularly with respect to climatic conditions, pavement configurations, and operational practices. These contextual dependencies may limit the availability of directly comparable studies across regions, climates, and application scenarios. Accordingly, the findings presented in this review should be interpreted within the defined scope of this narrative synthesis, rather than as an exhaustive or systematically pooled assessment of all published research on the topic. For consistency and clarity, this review adopts standardized terminology throughout the manuscript. The term porosity is used for general discussion of pore structure, VV is used to denote air-void content, permeability refers to the intrinsic hydraulic property of the material, infiltration denotes measured water-entry behavior at the surface, and cooling performance is described using metrics that reflect the governing mechanism, magnitude, and persistence of temperature reduction.

2. Fundamentals of PA Pavements

2.1. Structural and Material Characteristics

PA is an open-graded asphalt mixture in which the coarse aggregate skeleton is proportioned to preserve a continuous void network throughout the layer, thereby enabling hydraulic functionality [11,12]. Within the referenced literature, PA is typically characterized by relatively high porosity, generally exceeding 15% and commonly reaching approximately 18% or higher in open-graded structures [11,12]. Aggregate gradation governs stone-on-stone contact and therefore controls both the total void volume and the continuity of pore pathways within the mixture [12–14]. Mixtures with similar total VV content may nevertheless exhibit different pore connectivity and network topology, which can significantly influence both hydraulic and mechanical responses [15,16]. Computed tomography (CT)-based characterization is widely used to evaluate pore structure together with volumetric VV measurements [14,15], while image-based methods provide complementary evaluation of pore distribution and connectivity [16,17]. Figure 2 illustrates the

meso-structural basis of PA function by showing the aggregate skeleton, binder film, interconnected voids, temporary water storage, and downward infiltration pathways discussed in this subsection.

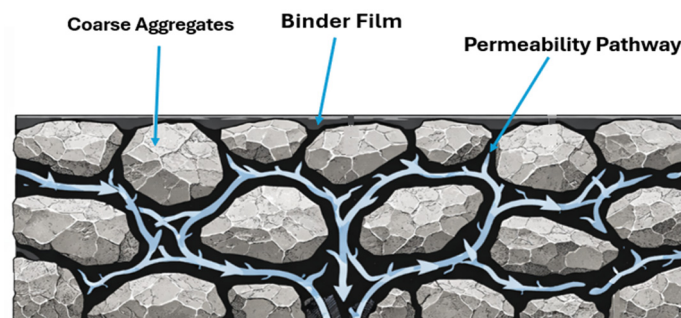


Figure 2. Schematic meso-structure of PA pavement showing the aggregate skeleton, thin binder film, interconnected void network, temporary water storage, and downward infiltration pathways.

Binder selection plays a critical role in controlling drain-down behavior, maintaining permeability stability, and ensuring long-term durability [18,19]. The open and interconnected void structure of PA increases binder exposure to air and water, making the mixture more vulnerable to oxidative aging and durability loss [11,20] and increasing susceptibility to drain-down and raveling [13,20]. To address these functional and durability demands, modified asphalt binders are commonly used in PA mixtures, including polymer-modified, high-viscosity, and rubber-modified binders [11,19,20]. Typical binders used in PA include polymer-modified systems such as styrene–butadiene–styrene (SBS)-modified asphalt and high-viscosity binders designed to resist drain-down and enhance durability under high VV conditions. Fiber-assisted systems are also frequently incorporated to improve binder stability and mixture durability [13,19]. These binder systems enhance aggregate–binder adhesion, moisture resistance, rutting performance, and overall mixture stability in PA applications [11,13,19]. The mixture design constraints and performance requirements therefore emphasize the co-optimization of gradation and binder system selection rather than maximizing void content alone, as reflected in the structural, volumetric, and hydraulic design ranges summarized in Table 1 [21,22]. Typical performance indicators include tensile strength ratio (TSR), drain-down resistance, and rutting resistance.

Table 1. Structural, volumetric, and hydraulic design parameters of porous and open-graded asphalt mixtures.

Parameter	Reported Value(s) with Clarification
Porosity regime	Porosity [ϕ] is reported as $>15\%$ and commonly $\geq 18\%$ for porous/open-graded asphalt [11,12]
VV content, VV (candidate gradations)	Three gradations yielded VV values of 15.90%, 18.33%, and 17.87% [13]
VV content, VV (CT-based PA concrete (PAC) variants)	PAC-13: 16.36–23.05%; PAC-20: 18.56–24.29% [14]
Connectivity threshold for drainage	Connected pores and favorable permeability were reported at VV $\approx 17.3\%$ or higher [15]
VVs used for pore/flow analysis	17.1%, 18.9%, 20.6%, and 22.7% [15]
3D reconstructed void volume	VV = 18.1% with total VV volume 49,635.7 mm ³ [15]
Permeability level	>100 m/day for open-graded specimens under the reported method [13]
Design acceptance criteria	VV $> 18\%$, Cantabro loss $< 20\%$, drain-down $\leq 0.3\%$ [13]
Semi-flexible substrate targets	VV about 25%, drain-down $< 0.3\%$, minimum permeability 100 m/day [21]
Polyurethane–asphalt design target	Target VV 20%; optimum asphalt-to-stone ratio 5.1% [18]
Drain-down and TSR criterion	Schellenberg drain-down 0.03–0.51%; TSR threshold 75%; target VV 20% [19]
Permeability values (one dataset)	Vertical permeability: 1.07 cm/s for high-viscosity binder (HVB) and 0.87 cm/s for HVB + polyester fiber; transverse permeability: $1.86\text{--}2.14 \times 10^{-2}$ cm/s [19]
Optimum asphalt content (OAC) and modifier dosages	OAC 4.50–5.38%; SBS 1–5% by binder weight; polypropylene fiber 5% [20]
Hydraulic–mechanical example pair	Permeability 0.394 cm/s; resilient modulus 3494 MPa [22]

PA design depends on achieving a balanced relationship between hydraulic functionality and mixture stability. Drainage continuity begins to deteriorate below approximately 17% VV, and practical design guidance therefore typically targets values exceeding 18% VV to maintain a safety margin above the connectivity threshold [13,15]. A permeability value near 100 m/day is similarly regarded as a practical lower limit for effective drainage performance, as lower permeability levels tend to shift the system toward slow filtration behavior rather than rapid drainage [13]. Nevertheless, increasing VV beyond recommended ranges is not necessarily advantageous, because higher void contents can promote binder drain-down and reduce mixture stability [19]. For this reason, semi-flexible or open-graded substrates may adopt higher void levels, around 25% VV, to facilitate grout acceptance, whereas conventional PA mixtures are commonly maintained within the range of approximately 18–20% VV to preserve cohesion and resistance to raveling [18]. Overall, the design objective is not defined by a single threshold value, but rather by an optimized balance among connectivity, permeability, constructability, and long-term durability requirements [21].

2.2. Functional Principles

PA achieves its hydraulic function through an interconnected VV network that enables rainfall to infiltrate into the layer and thereby reduces direct surface runoff generation [23]. Reported VV contents for PA are commonly above 20%, and specification ranges have been reported between 14 and 32% depending on the adopted standard [23]. Drainage from PA can be described as a storage–discharge process using a linear-reservoir representation in which a storage constant governs outflow recession following rainfall events [23]. Reported storage constants vary according to mixture characteristics and rainfall sequencing, ranging from minutes to several tens of minutes, with very slow cases exceeding 100 min under dry initial conditions and low runoff volumes [23]. Porous friction course (PFC) denotes thin PA overlays, typically 2.5–5.0 cm in thickness [24]. In PFC systems, water infiltrates rapidly into the porous layer and subsequently flows laterally along the underlying impervious interface toward the pavement edge [24]. Non-linear flow behavior has been observed under typical hydraulic gradients, supporting a Forchheimer-based interpretation rather than Darcy flow assumptions when estimating hydraulic conductivity [24]. Reported PFC effective porosity spans approximately 0.12–0.23, while hydraulic conductivity ranges from about 0.02 to 3.0 cm/s, indicating substantial variability in drainage capacity across systems [24].

Environmental Protection Agency Storm Water Management Model (EPA SWMM, Version 5.1; National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH, USA)-based rainfall–runoff simulations parameterized for PA have reported runoff-peak and runoff-volume reductions of roughly 20–30% for lower return-period events due to temporary water storage within the porous layer [25].

Cooling performance in pervious or porous pavements is governed primarily by moisture availability, because evaporation provides a latent heat sink that reduces surface temperature when water is present within the pore structure [26]. The evaporation resistance method (ERM) represents evaporative cooling through resistance terms associated with pavement moisture state and near-surface transport processes [26]. ERM results demonstrated a sharp increase in surface resistance when volumetric water content fell below 6.5% for ceramic brick and 11.8% for pervious concrete, indicating a threshold-type reduction in evaporative cooling potential as the surface dries [26]. When coupled with a one-dimensional heat-transfer model and validated against outdoor measurements, the reported agreement in surface temperature corresponded to root mean square error (RMSE)

values of 1.31 °C for ceramic brick and 1.64 °C for pervious concrete [26]. Under hot-humid summer conditions, one reported watering strategy targeted a morning application window of 07:00–11:00, although this timing should be interpreted as condition-specific rather than broadly generalizable [26]. Under the reported experimental conditions, watering at midday produced instantaneous surface cooling of up to 14 °C [26].

Figure 3 illustrates the thermo-hydrological cooling mechanism described above, demonstrating how stored pore water supports evaporation processes and reduces downward heat flux under surface energy loading conditions.

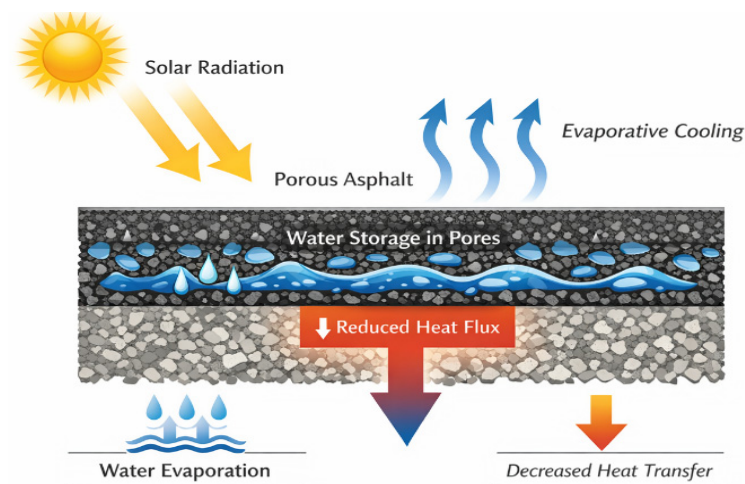


Figure 3. Thermo-hydrological cooling mechanism of PA pavement, showing solar radiation, stored water in interconnected voids, evaporative cooling, and reduced downward heat flux.

Taken together, these fundamentals indicate that PA performance depends primarily on pore-network quality rather than VV alone. A well-connected void structure is required to support infiltration and moisture redistribution, yet the same degree of structural openness can also increase the risk of drain-down and impose additional durability constraints [15,19,22]. The resulting design implication is that PA fundamentals inherently reflect a hydro-thermal trade-off: the system must remain sufficiently open to admit and transport water, while also maintaining adequate structural stability to preserve functionality under sustained service conditions [21,22].

3. Classification of PA

3.1. Conventional PA

Conventional PA is an open-graded wearing course designed to maintain a connected void structure that promotes rainfall infiltration and reduces surface runoff [27,28]. Unlike dense asphalt, PA preserves an interconnected pore network that supports water entry and drainage through the pavement system [27]. Review evidence further indicates that PA should be interpreted as part of a full-depth permeable pavement system in which the porous surface layer operates in conjunction with underlying aggregate layers that provide temporary storage and controlled drainage [28]. A cold-climate implementation reported a conventional PA mixture with 18% VV, 5.8% asphalt content, and performance-grade (PG) 64-28 binder, and the monitored system produced no measurable surface runoff during the observation period [29]. Guidance discussed in the reviewed literature also indicates that hydraulic behavior depends on the full pavement section rather than the surface layer alone, with reported drawdown periods in cited guidance sources extending up to 48–72 h. However, such values should be interpreted as guidance-based ranges rather than universal design thresholds, and the associated baseline context is summarized in Table 2 [28].

Table 2. Baseline functional characteristics and system guidance context for conventional PA pavements.

Parameter	Value (Units)
Functional basis of conventional PA	Open-graded porous surface designed to maintain an interconnected drainage network [27]
System interpretation	PA surface over underlying aggregate storage and drainage layers [28]
Example conventional PA mix (cold-climate application)	18% VV; 5.8% asphalt content; PG64-28 [29]
Reported drawdown guidance in reviewed literature	Up to 48–72 h [28]

Conventional PA commonly demonstrates high initial infiltration capacity, although long-term performance is influenced by both mixture permeability and section-scale factors such as slope and drainage geometry [30,31]. Under controlled testing conditions, infiltration declined from 96% to 87% as slope increased from 0% to 10%, as summarized in Table 3, indicating that hydraulic capture is sensitive to geometric conditions even under comparable rainfall loading [30]. Modeling studies have likewise identified porosity, permeability, layer thickness, and drainage path length as key controls governing drainage response [31]. Field evidence further demonstrates progressive hydraulic deterioration with service exposure and clogging, with the principal modeling and field findings compiled in Table 4. Nevertheless, runoff control may remain substantial during partial performance decline, with one monitored system still infiltrating 99.5% of storm inflow despite evidence of clogging effects [32–34]. Overall, conventional PA should be interpreted as a drainage-oriented pavement system, the initial hydraulic performance of which is strong but gradually reduces over time as clogging processes accumulate under service conditions [30–35].

Table 3. Laboratory-scale infiltration performance of conventional PA under controlled rainfall and slope conditions.

Parameter	Value (Units)
Fraction of applied water infiltrated over 0.50 m PA length at 0% slope	96% [30]
Fraction of applied water infiltrated over 0.50 m PA length at 10% slope	87% [30]
Simulated rainfall intensity used in the infiltration characterization	47.7–47.9 mm/h [30]

Table 4. Hydraulic performance degradation, drainage sensitivity, and clogging effects in conventional PA systems.

Parameter	Value (Units)
Porosity range used in drainage-performance modeling	18–25% [31]
Permeability coefficient range (k) used in modeling (single layer)	0.5–1.6 cm/s [31]
Drainage layer thickness and drainage path length evaluated in modeling	Thickness: 4–6 cm; drainage path length: 10–22 m [31]
Reported parameter-drainage association in modeling	Correlation exceeding 0.6 [31]
Drainage-performance degradation linked to porosity reduction (model result)	20–45% [31]
Maintained PA infiltration rate (field monitoring, 2011–2015)	Declined from 118 mm/min to 39 mm/min [33]
Unmaintained PA infiltration rate (field monitoring, 2011–2015)	Declined from 134 mm/min to 54 mm/min [33]
Storm inflow infiltrated based on field water balance	99.5% [33]
Taipei PA infiltration rate change at two sites (about 10 months)	Declined from around 1.5 cm/s to around 0.5 cm/s [34]
New-condition permeability and post-clogging reduction (controlled test, PA-16)	0.012 m/s (new); 64.16% reduction after clogging [32]
Clogging heterogeneity (controlled test): contrast between clogged vs. less-clogged zones	42.50% [32]
Residual runoff after clogging (controlled test): slopes up to 5%	Below 1% [32]
Maintenance implication (systematic synthesis)	Maintenance mitigates clogging; benefits drop when the surface becomes effectively impermeable [35]

Conventional PA is designed to maintain interconnected voids that facilitate water entry and drainage, in contrast to dense asphalt systems [27,28]. Field evidence from cold-climate applications further demonstrates that complete runoff elimination can be achieved under appropriate design and operational conditions [29]. Nonetheless, such outcomes reflect the integrated performance of the full porous pavement system, including storage and drainage layers, rather than the hydraulic function of the porous surface layer in isolation [29].

Infiltration remained the dominant response under both tested slope conditions, yet the reduction from 96% to 87% indicates that slope can directly diminish hydraulic capture even under nearly identical rainfall input [30]. Because the reported rainfall intensity remained essentially constant across the compared experimental runs, the observed decline in infiltration is more plausibly attributed to slope effects rather than to variations in hydraulic loading [30]. These findings were obtained under a relatively short flow length of 0.50 m and therefore should not be interpreted as direct evidence of drainage performance over longer field-scale flow paths [30].

Hydraulic decline in conventional PA is progressive and multi-factorial, with porosity loss, permeability variation, drainage path length, and clogging all contributing to reduced drainage performance [31–35]. Field and laboratory evidence shows that infiltration can deteriorate substantially over time, although event-scale runoff control may still remain high during partial hydraulic decline [32–34]. New-condition permeability or infiltration values should therefore not be interpreted as durable performance indicators without considering clogging progression, spatial variability, and maintenance condition [32–35].

3.2. Water-Retentive PA Systems

Water-retentive PA systems modify the open-graded asphalt skeleton by adding moisture-holding phases such as superabsorbent polymer (SAP)-based reservoirs or water-retentive grouts so that infiltrated water remains available for post-wetting evaporation rather than draining rapidly, thereby extending cooling persistence beyond conventional PA [36–38]. In these systems, VV remains important because it controls temporary storage and retained-water availability, with the corresponding VV–storage relationships summarized in Table 5, but higher VV alone does not guarantee better performance if structural stability or storage continuity is weakened [39,40]. Overall, modified retention-based PA performs best when added storage improves evaporative persistence without undermining the coupled hydraulic–structural function of the mixture [36–40].

Table 5. VV-dependent water storage and retention relationships in water-retentive PA systems.

Index (Unit)	Reported Relationship	Reported VV Range (%)	Reported Index Range (%)
Saturation storage (S_w) (%)	$S_w = 1.206 + 0.046 \cdot VV$ (fit 99.6%) [39]	17.22–23.91 [39]	1.99–2.30 [39]
Attached water (S_A) (%)	$S_A = 0.838 + 0.044 \cdot VV$ (fit 99.4%) [39]	17.22–23.91 [39]	1.59–1.88 [39]
Retained water after seepage (S_R) (%)	$S_R = 0.629 + 0.047 \cdot VV$ [39]	17.22–23.91 [39]	1.43–1.73 [39]

Water retention in porous systems depends on connected void space, so lowering VV too much reduces practical storage capacity [39]. Increasing VV can improve storage potential, but it may also weaken stone-to-stone contact and reduce service stability [40]. For retention-based systems, the main objective is not rapid drainage, but longer evaporative cooling after wetting, with representative wet-condition surface temperature reductions summarized in Table 6 [36]. This is especially important in semi-flexible water-retentive concepts, where effective performance requires a continuous storage phase, since disconnected voids can limit actual retention even when VV is high [38]. Overall, the evidence shows that higher VV alone does not guarantee better cooling persistence, because storage

gains are only useful when they do not undermine structural stability, making this trade-off context-dependent rather than governed by a single threshold [37,40].

Table 6. Reported surface temperature reductions in water-retentive and semi-flexible pa systems.

System/Design Lever	Reported Cooling Magnitude Under Wet Conditions
Semi-flexible water-retaining pavement (mortar infusion; PA framework reported 20–25% voids pre-infusion)	Surface temperature declines 17.7 °C during heating exposure and 21.9 °C during the cooling phase; cooling differences above 40 °C [36].
Water-retentive semi-flexible pavement with light-colored grout	Surface temperature reduction 19.6 °C (white), 9.7 °C (gray), 5.7 °C (black); reflectance maxima 76.81%, 35.97%, 17.35% (white, gray, black) [38].
SAP water-retaining asphalt (SAP–cement mortar moisture reservoir)	Cooling magnitude 10–12 °C [37].

The cited evidence shows that evaporative cooling becomes more pronounced under hotter surface conditions, with clearer differences appearing once surface temperature rises above about 40 °C in that specific setup, although this should not be treated as a universal threshold [36]. Cooling can remain active beyond the wetting period, as large peak temperature reductions were reported both during heating and in the subsequent cooling stage [36]. The cooling outcome is also affected by surface optical properties, since lighter grout produced greater reductions than darker grout under similar wetting conditions, and higher reflectance enhanced rather than replaced the evaporative effect [38]. In addition, SAP-based water-retentive systems consistently achieved measurable cooling of about 10–12 °C, while the corresponding service-feasibility indicators are summarized in Table 7, indicating that internal moisture storage can provide a stable and repeatable cooling response [37].

Table 7. Mechanical performance indicators of water-retentive and infusion-based PA configurations.

System	Reported Indicators
SAP water-retaining asphalt	Retained stability (RS)—based on Marshall stability % ≥ 88.2 ; TSR, % ≥ 81.8 ; rutting resistance 9336–10,552 passes/mm [37].
Water-retentive semi-flexible pavement with grout	Dynamic stability 6237–12,170 passes/mm; flexural strain discussed relative to 2500 $\mu\epsilon$ [38].
Grouted open-graded asphalt (infusion baseline)	Grouting/infusion reported to materially shift mechanical response in open-graded asphalt, supporting infusion-type system feasibility [40].

The reported evidence indicates that adding water-retention capacity does not necessarily reduce durability or high-temperature performance. In SAP water-retaining mixtures, the adopted moisture-resistance criteria and acceptable rutting ranges were still satisfied, although these results remain formulation-dependent [37]. In semi-flexible water-retentive pavements, grouting improved rutting resistance compared with unfilled PAC, showing that grout acts as a structural control in addition to a storage phase [38]. At the same time, flexural performance must still be checked against the 2500 microstrain criterion, so thermal benefits should not be considered separately from strain-based acceptability [38]. More broadly, infusion-based filling of connected voids can substantially alter mechanical response, which confirms that retention strategies must be evaluated as coupled hydraulic–structural systems rather than as cooling measures alone [40].

Taken together, the reported evidence shows that retention strategies can improve cooling persistence by preserving water within the system after wetting, but the mag-

nitude and durability of that benefit remain context-dependent because they vary with storage continuity, surface condition, optical properties, and formulation-specific mechanical acceptability [36–40].

3.3. Modified PA with Recycled Materials

Recycled and industrial by-product materials are increasingly being incorporated into PA to reduce virgin material demand while maintaining acceptable hydraulic and mechanical performance [41].

The cross-study hydraulic, mechanical, functional-surface, and environmental evidence for recycled and industrial-by-product-modified PA mixtures is summarized in Supplementary Table S1 [41–44].

Across recycled-content and by-product PA mixtures, hydraulic, mechanical, functional-surface, and environmental responses remain strongly system-dependent rather than being predicted by void content alone [41–44]. Reclaimed asphalt pavement (RAP) incorporation may still satisfy hydraulic criteria within the tested range, yet permeability can decline and mechanical response can vary depending on binder condition, aggregate characteristics, and warm-mix processing effects [41]. Functional coating approaches can preserve photocatalytic or water-repellent surface behavior, but these benefits do not necessarily indicate uniformly favorable performance as full material replacement strategies [42]. Environmental performance is likewise non-uniform, since some impact categories may improve whereas others, including global warming potential, may increase, and source-dependent RAP variability can further influence mixture behavior before optimization [43,44].

Accordingly, recycled PA should be selected through integrated hydraulic, mechanical, functional, environmental, and source-quality screening rather than on the basis of a single acceptable metric [41–44].

3.4. Pre-Wetted and Water-Charged PA

Pre-wetted (water-charged) PA is used to intensify short-term evaporative cooling by temporarily storing water within the connected void structure [45]. This stored water increases latent heat removal during hot periods and reduces sensible heating of the pavement and near-surface air [45]. Because open-graded systems can drain rapidly, the net cooling response is governed by the fraction of water that remains accessible near the surface and by the timing of wetting relative to peak insolation [45].

In these systems, cooling persistence depends on stored moisture that can remain available for evaporation beyond the initial wetting stage [36–38]. The benefit remains strongly water-dependent and is also constrained by structural feasibility, because storage-enhancing measures can alter mixture behavior and cannot be treated as purely thermal modifications [37,38,40]. These systems should therefore be interpreted as coupled hydraulic–thermal–structural interventions rather than as surface-cooling measures alone [37,38,40].

Supporting evidence from non-asphalt permeable pavements also showed immediate surface cooling of about 10 °C after sprinkling, with persistence of roughly 1–3 days and near-surface air-temperature reductions of 0.5–1.0 °C at pedestrian-relevant heights [46].

3.5. Hybrid PA Systems

Hybrid PA systems combine porous, moisture-enabled cooling with complementary thermal controls, including storage-based components and reflective pavement strategies [45,47,48]. This hybrid approach broadens thermal mitigation by linking evaporative cooling in permeable pavement systems with reflective-surface heat reduction, while recognizing that reflective performance remains site-dependent and must be judged against the local climate, urban morphology, and surrounding building conditions [47,48]. Reflective–evaporative hybrids can produce large surface temperature reductions under high solar

exposure [49]. However, the air-temperature response is usually smaller than the surface response [48,49]. Performance should therefore be assessed using both surface and near-surface air indicators [48,49]. Storage-augmented evaporative hybrids further aim to extend cooling persistence by retaining water and buffering heat within the system, which is relevant where drying occurs rapidly or where peak-temperature control is a priority [45]. Reflectance-focused surfacing layers remain compatible with porous or water-retentive concepts and are commonly treated as a modular hybrid component that can be combined with permeable structures to strengthen daytime cooling while maintaining drainage [46,50].

Climate-adaptive hybridization aims to modify not only peak temperature, but also the duration and depth of thermal loading through storage, structural optimization, and thermophysical tuning under different climatic and operational conditions, with representative thermal outcomes summarized in Table 8 [51,52]. These strategies must still satisfy mechanical and durability requirements and should be evaluated under representative wet and dry states rather than being judged from a single performance condition [52–54].

Table 8. Quantitative thermal outcomes and mechanical indicators for hybrid PA cooling technologies.

Hybrid Pathway	Design Parameter (s)	Quantitative Evidence (Selected)
Reflective and water-retentive hybrid [49]	Pavement reflectance 13% and 25%	Surface temperature reduction about 18 °C under high insolation. Surface cooling up to about 20 °C corresponded to near-surface air-temperature reduction of about 1 °C or less [49]
PA with water retention and latent storage	PA VV about 24%; saturated water absorption 44.1% (about 6.2 times the control); water retention 34.31% after 60 °C for 12 h [45]	Surface temperature reduction 9.3 °C under dry conditions and 11.6 °C under saturated conditions. Melting and crystallization enthalpies were 15.74 and 12.07 J/g, respectively [45].
Heat-blocking reflective surfacing (hybridizability layer)	Albedo 14% and 60% [50]	Surface temperature reduction about 16 °C relative to dense-graded asphalt. Urban simulation indicated air-temperature reduction > 0.8 °C at 60% albedo. Rut depth was about half that of dense-graded asphalt in airport taxiway application [50].
Reflective component benchmark (asphalt literature)	Titanium dioxide-based reflective approaches [46]	Mean cooling efficacy 10.97 °C. Mean albedo increase 80.28% with titanium dioxide inclusion [46]
Reflective and latent-heat storage hybrid (duration control)	Phase-change enthalpy about 177.2–177.3 J/g; enthalpy efficiency about 94.98%; quality retention 95.13% after 10 leakage cycles [52]	Average road surface temperature reduction 3.06 °C. Duration above 60 °C decreased by 50% during 12:00–22:00. Phase-change efficiency decreased by 6.5% after pressure aging vessel aging [52].

Thermal mitigation does not produce a single uniform benefit, since large surface temperature reductions may yield only limited pedestrian-level air cooling, and high-reflectance pavements can even worsen thermal comfort by increasing radiant heat despite cooler surfaces [48,49]. Under the cited modeled cases, stronger air-cooling response appeared at high albedo, but this should be interpreted as scenario-specific rather than a universal threshold [50]. Moisture-retentive and latent-heat systems mainly improve cooling persistence, with performance governed more by water availability, storage, and internal heat-transfer pathways than by peak surface reduction alone [45,51,52].

4. Cooling and Hydrological Mechanisms

4.1. Surface Cooling Mechanisms

Surface cooling in porous and water-retentive asphalt systems arises from the coupling of infiltration, storage, redistribution, and evaporation under the prevailing surface energy balance [36,55,56]. When water enters the connected pore structure, part of it is retained near the evaporation-active zone while part redistributes within the layer, supplying water for continued phase change and lowering surface temperature through latent heat consumption [36,55]. Cooling is usually strongest immediately after wetting and then declines as the surface dries and moisture transport shifts toward restricted internal redistribution and diffusion-limited evaporation [57,58]. Thus, the governing mechanism is not water intake alone, but how long stored water remains hydraulically accessible to sustain evaporation under changing external forcing [55,57–59].

The experimental and field evidence linking void structure, moisture retention, drying-stage behavior, and boundary conditions to surface cooling in porous and water-retentive asphalt pavements is summarized in Supplementary Table S2 [35,36,55–63].

Across porous and water-retentive asphalt systems, surface cooling is governed primarily by moisture availability, evaporation stage, and hydraulic accessibility of stored water rather than by permeability alone [35,36,55–63]. Higher void content can increase initial cooling magnitude, but rapid drainage may shorten the cooling window unless internal retention or water storage is sufficient to sustain evaporation [55,59,63]. The reported response also remains boundary-condition dependent, since surface temperature, shading, urban geometry, and time of day can modify both radiative forcing and the partitioning of sensible and latent heat [35,36,56]. This means that moisture availability and accessibility are more important to cooling persistence than permeability alone [35,36,55–63].

Cooling-oriented PA design should therefore prioritize retained, evaporation-accessible moisture rather than high permeability alone [55,57–59].

4.2. Hydrological Processes

PA and permeable asphalt systems control stormwater through three coupled steps: (i) infiltration through a connected void network, (ii) temporary detention within pavement or reservoir void space, and (iii) delayed drainage or outflow once storage approaches saturation [23,24]. Infiltration behavior varies with pore connectivity, available void space, and system configuration, whereas permeability is a material hydraulic property reported over a wide range for PA mixtures [24]. Layered permeable sections are used at the system scale to represent vertical percolation and detention [64]. A typical configuration includes a PA surface over an open-graded reservoir layer and underlying soil [64]. Time-dependent seepage observations confirm delayed flow-through within the layered profile [64]. Temporary water storage and post-drainage retained water govern both runoff initiation and drainage duration [23,24]. Field-informed analyses show that outflow begins after progressive filling of available void storage [23]. A residual fraction of infiltrated water can remain stored after rainfall ends, which supports delayed discharge rather than immediate runoff conversion [23,24]. Figure 4 illustrates the three coupled hydrological steps discussed in this subsection: infiltration through the connected void network, temporary storage within the pavement system, and delayed drainage or outflow as storage approaches saturation. These mechanisms produce measurable hydrologic benefits at the event scale, with the main system-scale thresholds for runoff onset, post-drainage retention, and event sensitivity summarized in Table 9 [25,65]. Field monitoring shows reduced effective outflow volumes and delayed peak discharge relative to conventional asphalt in most storms [65]. Modeling results show the same trend, with stronger reductions at higher permeable coverage and weaker reductions under higher rainfall intensity [25]. Evidence from urban infiltration

sensitivity further supports the importance of maintaining stable longer-term infiltration capacity, which exerts a stronger influence on reducing runoff coefficient and peak flow than changes limited to initial infiltration response [66].

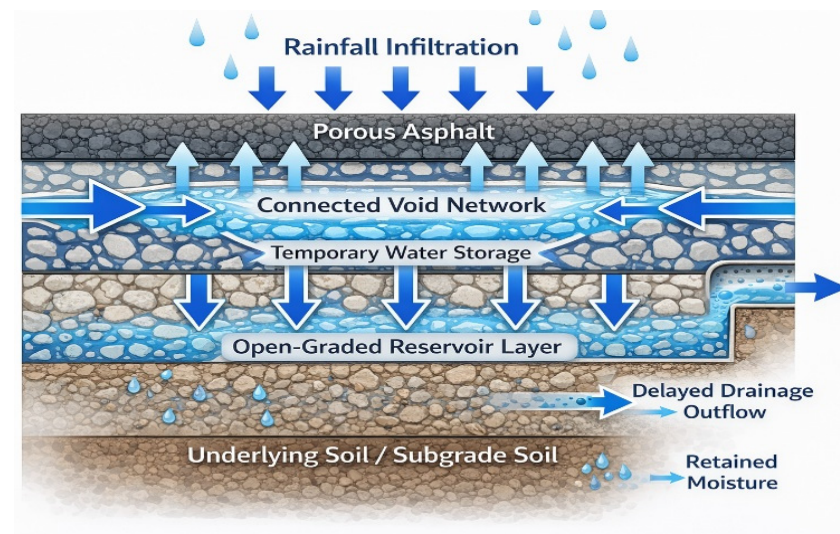


Figure 4. Cross-sectional schematic of rainfall infiltration, temporary water storage, and delayed drainage in a PA pavement.

Table 9. Hydraulic indicators of infiltration, storage, and runoff attenuation in PA systems.

Hydrological Process Component	Hydraulic Indicator and Experimental/Modeling Context	Reported Quantitative Outcome (s)
VV content and permeability (material-scale)	PA mixture properties: VV and hydraulic conductivity, k [24]	$\phi = 0.12\text{--}0.23$; $k = 0.02\text{--}3.0$ cm/s [24]
Infiltration pathway (laboratory system-scale)	Layered percolation-profile test on PAC over open-graded gravel, natural sand, and natural sand [64]	Void content = 20.1%; layer thicknesses = 6.3 cm PAC, 30 cm open-graded gravel, 15 cm natural sand over natural sand [64]
Water retention and storage capacity (runoff initiation threshold)	Field-informed drainage analysis relating runoff initiation to cumulative pore-volume filling in PA [23]	Runoff onset occurred after cumulative infiltration reached 25% of void volume [23]
Water retention and storage capacity (post-event residual)	Field-informed drainage or retention analysis of infiltrated water remaining after drainage [23]	Final retention commonly 10–25% of infiltrated water; reported range 14–29% [23]
Runoff reduction and peak flow delay (field monitoring; multi-technology permeable pavements with asphalt baseline)	Event-scale monitoring of permeable pavement cells against standard asphalt control [65]	Mean total outflow reduction: asphalt 35.70%, pervious concrete 43.88%, High-Open-Area PICP 66.29%, Low-Open-Area PICP 63.63%, (CPG) 37.68%; peak delay 34–35 min; no delay at depth 89 mm [65]
Water retention and storage capacity (field event threshold; multi-technology)	Rainfall depths associated with no outflow from selected permeable pavement cells [65]	Rainfall depths < 6 mm produced no outflow in selected events for PICP1 and plastic grid pavers [65]
Runoff reduction and peak flow response (modeling; PA)	EPA SWMM implementation of PA surface thickness = 50 mm; event-response sensitivity [25]	Peak or volume reductions = 20–30% for lower return-period events; reductions increased with higher PA area and decreased with higher rainfall intensity [25]
Storage-controlled transition (mechanistic; PA)	Conceptual storage-to-runoff behavior describing response after pore storage is exhausted [24]	Storage persisted until saturation; runoff increased once storage was exhausted [24]

PICP: Permeable Interlocking Concrete Pavement; CPG: Concrete Grid Pavers.

Hydrologic performance in PA is governed mainly by storage, not permeability alone, because the pavement first acts as a detention system and runoff begins only after sufficient pore storage has been filled [24]. Within the cited drainage framework, runoff started after

cumulative infiltration reached about 25% void-volume filling, which indicates a storage-related transition rather than a universal design threshold [23]. Even after drainage stops, about 10–25% of infiltrated water may remain stored, helping explain delayed outflow tails and the continued potential for post-storm evaporation [23]. Field monitoring also showed that some cells produced no outflow for rainfall depths below about 6 mm, suggesting that small storms can be fully retained when storage is still available, although this depends on antecedent moisture and pavement condition [65].

The cooling and hydrological mechanisms are coupled through the same storage pathway. Infiltration creates access to water, but retained moisture and its redistribution determine whether that water becomes sustained evaporative cooling or only short-lived drainage response [23,24,55]. PA should therefore be interpreted as a storage-regulated thermo-hydrological system, not as separate thermal and hydraulic functions [25,59].

5. Laboratory and Field Evaluation Methods

5.1. Laboratory Testing Approaches

Laboratory evaluation of PA cooling is used to resolve the coupled thermal and moisture controls that determine whether stored water can produce sustained surface temperature reduction. These methods capture heat-transfer behavior, water retention, drying kinetics, and pore-dependent evaporation pathways under controlled conditions, which makes them useful for parameterizing hydro-thermal response across materials [26,58,67]. Their main limitation is that simplified boundary conditions and process isolation do not fully represent the coupled storage, redistribution, evaporation, and external forcing that govern service-condition cooling [26,68,69].

The laboratory-derived thermal and moisture transport parameters used to interpret PA cooling behavior are summarized in Supplementary Table S3 [26,58,67–71].

Across laboratory studies, the reported response remains strongly test-dependent because effective thermal conductivity, evaporation resistance, and drying behavior vary with material structure, initial moisture condition, airflow, heating level, and prior conditioning or loading history [26,67–71]. Laboratory results should therefore be interpreted as controlled hydro-thermal indicators rather than direct predictors of field cooling performance, and they are most informative when hydraulic and thermal measurements are interpreted together because isolated parameters do not fully represent the coupled pore-water and heat-transfer processes governing cooling persistence [58,67–69].

5.2. Field Measurement Techniques

Field evaluation of PA cooling and drainage is usually based on combined thermal and hydrological monitoring under service conditions [29,34]. Across field studies, the main pattern is that PA often shows early runoff attenuation, measurable thermal response, and spatially variable intake behavior, while infrared thermography, embedded sensors, and infiltration testing help reveal heterogeneity that surface observations alone may miss [35,72]. However, most available datasets remain short-term or event-based, so they cannot reliably distinguish temporary response from durable hydraulic and thermal performance [29,33]. Early infiltration or cooling results should therefore not be treated as stable long-term indicators without considering clogging progression, maintenance condition, and meteorological variability [35,57]. This is consistent with broader climate-resilience assessments, which show that pavement adaptation should be judged against changing service conditions rather than isolated observations [73]. Longer-term repeated validation is therefore needed to determine whether these field benefits persist under service-life conditions [29,34].

The field and synthesis evidence linking infiltration decline, runoff response, thermal monitoring signals, and coupled long-term evaluation is summarized in Supplementary Table S4 [29,30,33–35,61,72,73].

Across field studies, PA performance is best interpreted as a time-dependent hydraulic–thermal response rather than a fixed as-built condition [29,30,33]. Runoff attenuation and thermal benefits can be observed in early or event-scale monitoring, but these responses do not by themselves confirm durable long-term function under progressive clogging, maintenance variation, and changing meteorological forcing [29,33,34]. Field interpretation also remains method-dependent, since infiltration tests, infrared screening, temperature monitoring, and runoff measurements capture different aspects of system behavior and are not directly interchangeable [34,61,72]. Accordingly, long-term field validation should focus on repeated and preferably standardized coupled monitoring to distinguish temporary response from sustained service-condition performance, while tracking persistence and deterioration trends rather than only initial runoff, infiltration, or cooling signals [29–35,73].

5.3. Performance Trade-Offs and Design Optimization

PA pavement design should be treated as a coupled hydro-thermal problem, not as separate thermal and hydrological targets [24,55]. Fast drainage alone does not guarantee long cooling duration, because cooling persistence depends on how much water remains in the connected void system after wetting [55]. Hydrological performance also depends on storage capacity, not on infiltration rate alone, and runoff reduction improves as storage increases until rainfall intensity or volume exceeds the available storage threshold [23,25]. This means the design should be checked under different rainfall conditions, and permeability should not be used as the only optimization target [23–25].

Another trade-off appears in clogging behavior. High void connectivity supports infiltration and internal moisture movement, but it can also increase sensitivity to sediment trapping in the surface and near-surface pores [74]. The clogging response is strongly controlled by the particle-to-void size relationship, where coarse particles tend to block upper pores and finer particles can penetrate deeper into the pore network [74]. Sediment ingress in PA progresses through a non-uniform clogging process rather than a single uniform blockage pattern [74]. Larger particles tend to accumulate within upper pore openings and near-surface voids, where they suppress infiltration by restricting water entry into the layer, whereas finer particles may penetrate deeper into the connected pore network and alter internal drainage pathways [74]. As clogging develops, hydraulic performance declines not only through lower intake capacity, but also through reduced pore connectivity, porosity, and drainage continuity [24,74]. Since evaporative cooling depends on the retention and redistribution of accessible moisture, rapid drainage or disrupted internal moisture movement can shorten cooling duration even when some void volume remains within the structure [24,55,74]. For this reason, clogging resistance should be included in design optimization from the beginning, not treated only as a maintenance issue after construction [24,74]. The design objective is balance rather than maximization of one parameter, so a practical approach is to select a permeability range that supports adequate infiltration capacity, then verify storage and moisture availability for cooling persistence, and finally check clogging susceptibility and service-life limits under realistic conditions [24,55,74].

This evaluation logic should not rely only on isolated laboratory indicators or initial post-construction values [23,24]. Repeated coupled validation is needed because runoff control, retained moisture, and cooling persistence change during service as field conditions evolve [23,24,74]. Multi-season datasets and standardized reporting strengthen optimization claims by improving comparison across studies conducted under different hy-

draulic, thermal, and boundary-condition definitions, and the resulting trade-off structure is organized in Table 10 [23,25,55].

Table 10. Trade-off axes, design implications, and optimization checks for coupled hydro-thermal performance in PA pavements.

Trade-Off Axis	Design Implication	Service-Condition Verification over Time
Permeability vs. cooling persistence	High permeability improves drainage, but cooling duration depends on retained moisture after wetting rather than rapid flow alone [55].	Verify both hydraulic response and post-wetting cooling persistence under field wetting and drying conditions, not from permeability alone [24,55].
Infiltration and storage vs. storm control	Infiltration alone does not represent hydrological performance, because runoff reduction also depends on internal storage and storm magnitude [23,25].	Check infiltration, storage-related response, and runoff behavior together under more than one rainfall condition and repeat evaluation after field exposure [23,25].
Void connectivity vs. clogging resistance	Higher void connectivity supports infiltration and moisture movement, but it can also increase sensitivity to sediment trapping and progressive performance loss [74].	Recheck hydraulic and thermal function after clogging develops, and do not assume that early-life benefit remains stable during service [24,74].
Initial efficiency vs. long-term serviceability	A mixture may perform well at the start yet lose balance between drainage and cooling as flow paths change over time [24,74].	Support optimization with repeated coupled field validation rather than initial laboratory or post-construction values alone [24,55,74].
Single-metric vs. coupled optimization	Maximizing one parameter can misrepresent overall performance when hydraulic and thermal responses diverge under service conditions [24,55].	Use a coupled validation framework that tracks hydraulic, thermal, and related field indicators together under documented boundary conditions and across seasons [24,55].

Evaluation methods are most useful when laboratory control and field validation are treated as complementary rather than interchangeable. Laboratory testing can isolate transport thresholds and drying behavior, but field monitoring is needed to confirm whether those mechanisms persist under seasonal exposure, clogging, and variable wetting histories [24,26,33]. Performance claims are therefore strongest when hydraulic and thermal indicators are interpreted together over time, not from a single metric or a single testing domain [24,55,74].

6. Influence of Environmental and Climatic Conditions

Environmental forcing governs whether stored moisture can be converted into useful evaporative cooling and how long that effect can be sustained [75,76]. In addition to field and laboratory evidence, simulation research has become important for interpreting this dependence because it can isolate the coupled effects of radiation, air temperature, relative humidity, wind, wetting schedule, and pavement moisture transport under controlled boundary conditions [6,75]. Numerical studies therefore complement measurements by extending evaluation from observed events to scenario-based assessment of cooling duration, water demand, and climatic sensitivity [61,75]. Figure 5 summarizes the simulation-based framework used to assess PA pavement under environmental and climatic conditions, showing how atmospheric forcing and pavement properties control coupled thermo-hydrological processes and the resulting performance indicators.

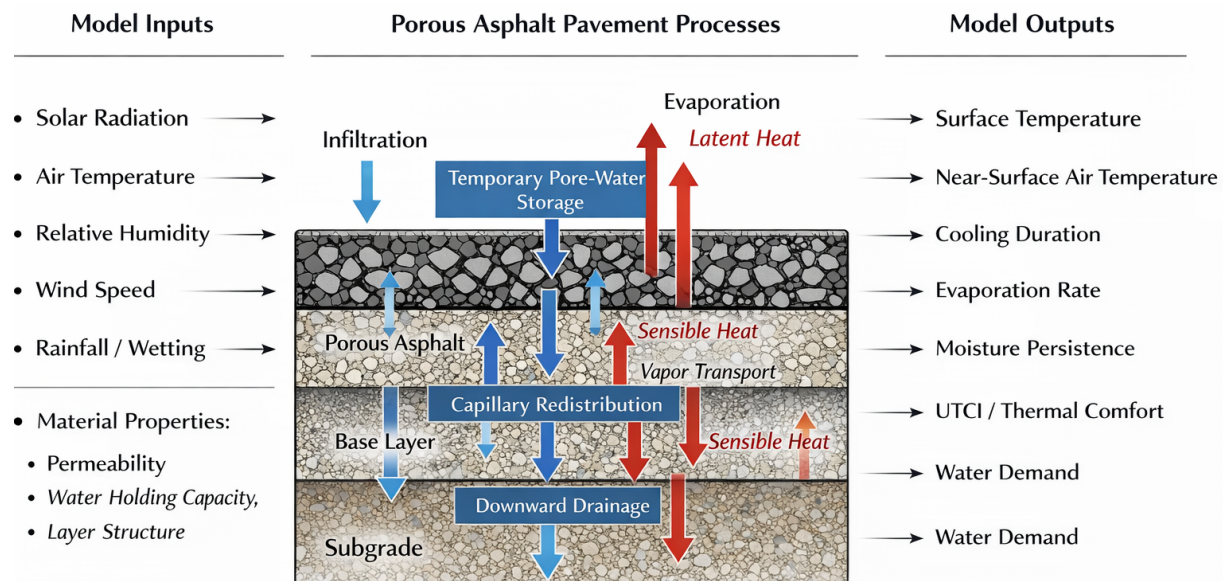


Figure 5. Simulation-based assessment framework for PA pavement under environmental and climatic conditions. UTCI refers to the Universal Thermal Climate Index, used here as an indicator of outdoor thermal comfort conditions.

Watering-based cooling depends on boundary conditions and on how forcing and measurements are defined [75,76]. Under insolation, optimized watering cycles reduced water use by more than 80% while reducing cooling magnitude by less than 13% [76]. Under the same conditions, measured evaporation rates were 0.31–0.41 mm/h [76]. Smart-wetting modeling treated temperature, relative humidity, and wind as direct control variables, with tested ranges of 22–35 °C, 30–80% relative humidity, and 10 m wind speeds increasing from 0.6–2.8 m/s to more than 4 m/s [75]. The same framework identified about 6 mm/day applied over 10 min in the morning between 08:00 and 10:00 as an effective scenario for balancing cooling and water use under the modeled conditions, rather than as a generally recommended operating rule [75]. These results show that simulation can identify operating windows for wetting strategies that are difficult to define from field observations alone [75].

Microclimate responses are concentrated close to the pavement surface, so sensor height and near-surface exchange conditions should be reported as part of performance evidence [60,76]. Field monitoring across permeable pavements with different hydraulic properties showed that irrigation primarily cooled and humidified air within 30 cm above the surface [60]. The same evidence indicated that cooling persistence depends more on retained water availability than on permeability alone, because higher permeability accelerates drainage and shortens the wet-state duration [60]. Under irrigated conditions, the average UTCI difference between a permeable brick and an impermeable reference decreased by 0.4 °C [60]. In the same comparison, PA and pervious concrete systems emphasizing permeability did not show a notable thermal improvement in the surrounding environment [60]. Additional field evidence reported that sprinkling reduced sensible-to-net-shortwave ratios and improved pedestrian-level heat-stress indicators, including black globe temperature and wet-bulb globe temperature [77]. Street-canyon experiments further showed that local geometry modifies thermal response, which supports the use of simulation tools for examining morphology-dependent cooling under controlled urban configurations [61].

At seasonal scale, subsurface thermal behavior contributes to persistence and depth of thermal influence [66]. Thermal performance should be reported using explicit forcing descriptors, including radiation exposure, air temperature, relative humidity, wind or ven-

tilation, and wetting timing [6,78]. This interpretation is consistent with climate-resilience reviews showing that pavement assessment under changing climate conditions increasingly relies on predictive and scenario-based approaches [6,73]. Rutting-resilience assessments similarly indicate that future performance cannot be separated from projected climatic loading [78]. At the urban-network scale, pavement interventions also interact with street forms and other mitigation measures under similar meteorological backgrounds [79]. Street-canyon evidence supports this dependence at local scale in hot and humid climates [61]. Hydrologic boundary conditions determine when evaporative cooling is feasible, because rainfall, infiltration variability, and cold-climate stormwater functioning control rewetting frequency and moisture persistence [29,71]. Meteorology-dependent strategies such as watering should therefore be scaled using operating rules consistent with local water availability, maintenance capacity, and decision priorities [75,76,80].

Environmental forcing does not merely modify PA performance; it determines when hydro-thermal benefit is feasible at all. The same pavement can show different cooling and runoff behavior under different radiation, humidity, wind, rainfall, and rewetting conditions, so results should not be transferred across climates without explicit forcing descriptors [60,75,76]. Climate-responsive operation is therefore part of performance design, not an external adjustment made after material selection [6,78,80].

7. Practical Implementation Challenges and Long-Term Performance Risks

Section 5.3 established the coupled optimization logic of PA systems, but practical deployment depends on whether that balance can be maintained under real service conditions [24]. After construction, the pore network that supports infiltration and evaporative cooling is exposed to clogging, repeated wetting and drying, and progressive mechanical deterioration [74]. Implementation should therefore be guided by the intended service objective. Systems aimed mainly at runoff control may prioritize rapid intake and discharge, whereas systems intended to support heat mitigation must also preserve sufficient near-surface moisture to sustain evaporation during operation [24,34,60].

Cooling performance must be judged by both cooling magnitude and cooling persistence, not by peak temperature reduction alone [75,76]. Pre-wetted and water-charged systems can produce clear short-term cooling, but the persistence of that effect depends on retained water, atmospheric demand, and wetting timing [60,75,76]. This helps explain why drainage-oriented PA, retention-enhanced PA, and hybrid systems do not show the same thermal response even when all remain hydraulically functional [34,60]. In practice, the design objective must therefore be defined clearly. Systems intended for heat mitigation must also preserve moisture close enough to the surface to sustain evaporation over the required cooling period [24,34,60].

Another key trade-off concerns thermal benefit versus durability and structural reliability. Hydro-thermal function depends on water availability, yet repeated wetting and drying can alter binder-scale and mixture-scale behavior and accelerate damage progression [70,81]. Cooling-oriented operation should therefore not be assessed separately from structural performance under repeated moisture exposure and traffic loading [70,71]. Functional additives and retention-enhancing concepts may improve one target, but they can also introduce mechanical, compatibility, or durability limits if they are not evaluated under coupled moisture–temperature conditions [71,82]. The most reliable systems are therefore those that balance drainage, moisture retention, and structural resistance within one design framework [34,60].

Maintenance realism is equally important because many PA systems show strong initial hydraulic and thermal performance, then lose efficiency when inspection and cleaning

are delayed [24,83]. In PAC, sediment deposition alters internal flow paths and gradually reduces effective permeability, even when the original mixture design is appropriate [74,83]. This decline is not only hydraulic. Partial blockage can also reduce rewetting efficiency and moisture redistribution, which weakens evaporative cooling before infiltration capacity is fully lost [24,60,74]. Maintenance should therefore be treated as part of the design strategy, not only as a post-construction requirement [24]. Surface structure should be selected with the expected sediment type, loading rate, and cleaning feasibility of the target site in mind [74].

These constraints also explain why results differ across studies. Some studies assess systems designed for rapid hydraulic conveyance, while others evaluate retention-based or wetted systems intended to prolong evaporation [34,60,75]. Thermal response also depends strongly on radiation, air temperature, humidity, wind, and wetting schedule [60,75,76]. Field performance is therefore shaped not only by mixture design, but also by climate, exposure history, and maintenance conditions. A robust implementation framework should accordingly combine hydro-thermal performance indicators, clogging susceptibility, structural acceptability, and maintenance planning so that runoff control and thermal mitigation can be sustained together over time [24,25,74].

Long-term PA performance depends on whether hydraulic access, moisture availability, and structural acceptability can be sustained together under real service conditions [24,25,74]. This is why implementation outcomes differ across studies: the controlling variable is not mixture design alone, but the interaction among climate, sediment loading, wetting history, and maintenance realism [34,60,75]. Practical deployment should therefore be based on service-life balance rather than on strong initial performance alone [24,74,83].

8. Conclusions and Recommendations

PA pavements are no longer viewed only as drainage layers, but as multifunctional systems that influence both runoff control and surface thermal behavior through coupled moisture–energy processes. This review synthesized current knowledge on PA types, governing mechanisms, evaluation methods, climatic controls, and service-life limitations relevant to urban climate resilience. The following conclusions and recommendations can be drawn:

- PA cooling depends mainly on moisture availability within the connected void structure, since evaporation cannot be sustained when water drains too rapidly or is not retained near the surface.
- Hydrological performance is controlled by pore connectivity, storage capacity, and system configuration, which together govern infiltration, detention, and runoff attenuation.
- Thermal and hydraulic benefits should be interpreted as system-dependent, because reported outcomes vary with mixture design, wetting condition, climatic forcing, and measurement method.
- High permeability alone does not ensure durable cooling, as long-term performance also depends on retention, resistance to clogging, and maintenance condition.
- Field performance must be assessed carefully, since surface cooling does not always translate into equivalent air-cooling benefit under real urban conditions.
- Practical implementation requires balancing cooling, drainage, durability, and maintenance demands rather than maximizing a single property.

These findings also highlight several priorities for future research:

- Long-term field studies that jointly track temperature, moisture, infiltration decline, and clogging progression under service conditions.

- More standardized hydraulic and thermal testing and reporting methods to improve comparison across studies.
- Validated coupled hydro-thermal models that connect material-scale properties with street-scale performance.
- Performance-based design approaches that relate target cooling and runoff benefits to pore structure, retention behavior, and maintenance needs.
- Integrated assessment frameworks that evaluate hydro-thermal gains together with durability and operational feasibility.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su18083836/s1>, Table S1: Cross-study hydraulic, mechanical, functional-surface, and environmental evidence for recycled and industrial by-product modified PA mixtures; Table S2: Experimental and field evidence linking void structure, moisture retention, drying-stage behavior, and boundary conditions to surface cooling in porous and water-retentive asphalt pavements; Table S3: Laboratory-derived thermal and moisture transport parameters used to interpret PA cooling behavior; Table S4: Field and synthesis evidence linking infiltration decline, runoff response, thermal monitoring signals, and coupled long-term evaluation.

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