

Balancing Hydrological Performance and Structural Capacity: A Comparative Review of Permeable Pavement Systems for Urban Stormwater Management

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Research Article

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BALANCING HYDROLOGICAL PERFORMANCE AND STRUCTURAL CAPACITY: A COMPARATIVE REVIEW OF PERMEABLE PAVEMENT SYSTEMS FOR URBAN STORMWATER MANAGEMENT

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Abstract

Permeable systems are an efficient solution for preventing flooding risks and managing stormwater by allowing precipitation to infiltrate through the pavement into the soil. Beyond their hydrological benefits, these systems enhance water quality by removing pollutants, including microplastics and inorganic materials. However, System performance can vary based on type and mixture. Some common variants implemented worldwide include Porous Asphalt Pavement (PAP), Permeable Concrete Pavement (PCP), and Permeable-Interlocking Concrete Pavers (PICP). Furthermore, many issues revolve around these systems, including clogging, frequent maintenance checks, and poor performance due to an imbalance between porosity (%) and compressive strength (MPa). This review addresses design inputs, including layer thickness, aggregate size, and recycled materials, and compares them to performance variables, such as durability, infiltration, porosity, and compressive strength. Additionally, an early summary of permeable technology, including diagrams, is incorporated to enhance understanding of intent and benefits. These methods will assess the efficiency of each system and the trade-offs that will need to be weighed when deciding between alternatives. This review integrates existing methodologies to determine rough estimates of cost-benefit analytics in various porous systems, analyzing permeability, void structure and limitations to suggest where certain alternatives are most durable. These systems are evaluated for their practicality in urban infrastructure designs as a long-term, sustainable alternative technology in alignment with Sustainable Development Goals.

Keywords:

permeable systems, porous asphalt pavement, permeable concrete pavement, cost-benefit, permeable-interlocking concrete pavers, limitations, porosity, maintenance, clogging, infiltration, compressive strength, urban, sustainability, trade-offs

INTRODUCTION 1

1.1

New and more efficient infrastructure is being built all over the world as a result of urbanization, expanding at an uncontrollable pace. In fact, by 2050, the amount of building floor space is expected to double as a result of fast-rising economies (UNEP, 2025). From a societal perspective, this rapidly emerging pattern of urbanization is monumental, as it will initiate an increase in housing, warehouses, offices, and transportation (UNEP, 2025). With the rapid growth of urbanization, particularly in the 20th century, massive landscape changes have been made worldwide. These contribute to an even more critical matter known as climate change. With constant construction on the rise, the focus on environmental protection becomes significantly more complicated and demanding, interfering with the advancement of infrastructure. In a 2023 data report, the buildings and construction sectors were easily the largest emitters of greenhouse gases, accounting for approximately 37% of all global emissions (UNEP, 2023). However, these sectors have improved in the past couple of years and are expected to decrease emissions by 50-75% of the total sector emissions in the next couple of decades. At this rate, this gradual expected change remains too slow for greenhouse gas emissions to reach a sustainable point in the upcoming years.

To further understand the roots of these emissions, we must look at concrete, an essential material used in most infrastructure (Adesina and Zhang, 2024). Studies done in late December 2024 state that concrete is responsible for 7% of global carbon emissions, having a footprint larger than most countries, including India and even the entire EU (European Union) region, only trailing behind China and the U.S. (Bandera, 2024). In turn, persistent increases in carbon emissions have been accompanied by an ongoing rise in global sea levels. According to data compiled by Rebecca Lindsey (2024), the global sea level has risen from 44.57 mm (December to February 2010) to a staggering, estimated 80.86 mm (September - October 2024). It's expected to continue at this rate as a result of melting glaciers and ice sheets, along with seawater expanding as it warms (Lindsey, 2023). Across the United States, roughly 30% of the population lives in coastal areas, where many people are vulnerable to these flooding and storm hazards (Lindsey, 2023). Global warming and urbanization, being the leading causes of these coastline issues worldwide, suggest a focus on sustainable and efficient infrastructure materials, mainly targeting concrete and asphalt (Ramsden, 2020).

1.2

Currently, impermeable pavement materials, such as asphalt and concrete, are used in roads, sidewalks, and other city infrastructure, meaning rain cannot penetrate the surface of the ground. During rainfall, these pavement materials block natural infiltration, which forces water to accumulate on sidewalks and roads (ScienceDirect, 2024). As water cannot infiltrate, surface runoff increases rapidly, and the drainage system is overwhelmed by the extreme and intense amount of rainfall it cannot handle, resulting in urban flooding, traffic disruption, and an increased possibility of vehicle accidents (Morgan Pavement, 2023). Statistics indicate that road networks experience the highest rates of damage during periods of urban rainfall and flooding (Zhang et al., 2025). Furthermore, the runoff water acts as a transporter of contaminants. This includes oils, tire particles, and dust across pavements, directly carrying contaminants to lakes and coastal waters. This contaminant process notably decreases the quality of urban water and introduces contaminants into aquatic systems (EPA, 2005; Princeton

Science Communication, 2020). Considering the rising frequency of extreme weather due to climate change, conventional impermeable pavement no longer meets the needs of flood management. Cities are facing a major challenge in designing a sustainable urban environment.

1.3

Water-absorbing pavement, also referred to as permeable or pervious pavement, is now emerging as a solution to the issues addressed. Permeable pavement is a unique type of concrete that allows water from precipitation and other sources to pass directly through it. This reduces the collected surface runoff from a site by allowing natural groundwater recharge instead (Interactive Construction, n.d.). The Municipal guideline outlines the materials for permeable pavement: a hard surface material with large pore spaces or voids that allow water to move through the paving material; and a crushed stone bedding and base layer that supports the pavers while allowing water to drain away (District of Saanich, n.d.). In addition, the Municipal guideline reports several surface material options: Concrete Unit Pavers (with grass or gravel infill), Porous asphalt, Porous concrete, and Plastic grid systems (District of Saanich, n.d.).

1.4

Numerous studies have shown the advantages of permeable pavement. The many studies on porous asphalt have shown that these pavements significantly reduce surface runoff; increase groundwater and aquifer recharge; and raise the water table by collecting rainfall and allowing it to infiltrate. They effectively utilize waste materials such as fly ash, thus making this technique more eco-friendly (IJERT, 2020). Furthermore, the U.S. Environmental Protection Agency reports that porous pavement improves road safety due to better skid resistance, removes pollutants from water, and requires less maintenance for curbing and storm sewers (U.S. Environmental Protection Agency, n.d.). These hydrologic improvements decrease the likelihood of stormwater runoff and flooding during heavy rain. The effectiveness of permeable pavement is proven by the study of Rodríguez-Hernández et al. (2017). The permeable pavement achieved over 70% efficiency, which indicates that the permeable pavement infiltrated 70% of the water. Further, the pavement also slows down the water flow velocity, which prevents drainage system overload. From an economic perspective, the permeable pavement reduces the costs for the sewer system because it absorbs water, lowering the operating costs.

Existing products and implementations of permeable pavement put up powerful evidence for its effectiveness. For instance, TRUEGRID Paver's water-absorbing pavement, made from 100% recycled plastic, also lessens the burden on local sewer systems, especially critical in urban areas. TRUEGRID's design works by using stabilized gravel over a gravel sub-base to drain stormwater directly through the pavement and into the soil below (TRUEGRID, n.d.). Minnesota initiated a huge implementation of permeable pavements as part of a 2009 stormwater quality project to protect Lake Owasso. The following benefits were revealed: reduced snow and ice buildup in winter, decreasing the reliance on road salt, and avoiding the construction of stormwater infrastructure (Walker, 2023). Additionally, companies such as NACTO, Hydro Pavers, The Conservative Foundation, and Morgan Pavement have developed a range of innovative models that further expand the technology's real-world applications and widespread adoption.

1.5

Some limitations of permeable pavement systems must be carefully considered before further enhancements. Permeable pavement requires frequent maintenance checks regarding the removal of sediment and other materials. These constant checks involve evaluating drainage systems for clogging and functionality, as well as damage inspections for cracks that interfere with the filtration of water (Kathale et al., 2023). In relation to these issues, chemical substances, like vehicle fuel, can leach from the asphalt, contaminating groundwater depending on soil conditions. Further scientific data will be required for permeable pavement technology to deal with these pollutants (e.g. nitrates, chlorides) by absorbing or trapping any unwanted chemicals that move through the soil (U.S. Environmental Protection Agency, 1999).

With these advancements, another significant drawback is cost and affordability. According to an EPA stormwater fact sheet, an estimated cost for a porous pavement system is an immense \$41,073 (per project), which doesn't account for maintenance and other technological issues that may occur. For a porous pavement parking lot, the annual estimated program cost is \$200 per acre yearly, which consists of the expenditure of four inspections annually and vacuum sweeping treatments. Due to a high cost, many current innovations of permeable concrete are limited to sidewalks, parking lots, and low-volume roadways (Pal et al., 2020). The US Environmental Protection Agency (USEPA) recommends that permeable concrete be installed only in soils with low clay content (<30%), flat slope areas (<5%), and deep permeable soils far away from drinking water, reducing risks of contamination or other chemical leaks (Dreelin et al., 2006). Additionally, studies show that permeable concrete is not suitable on slopes greater than 8%, on high-speed transportation routes, or in any areas with high water tables (< 1.0 m deep). According to the District of Saanich, drainage check dams are required on slope grades greater than 5%, which explains the USEPA concerns and regulations on these systems. These limitations cause hesitation in technological funding and engineering processes, preventing permeable systems from taking over urbanized roads.

1.6

The purpose of the research is to explore how urbanized cities across the world can implement highly efficient, permeable systems, an impactful contribution to the prevention of global warming and coastal urban flooding. By integrating porous pavements into modern infrastructure (i.e. sidewalks, parking lots, roadways), cities can prevent flooding, reduce infrastructure damage, and promote a more sustainable urban water cycle.

The report uses prior data and information from secondary credible sources to analyze the functionality, materials, costs, and environmental impacts of water-absorbing pavements. From the collective data, water-absorbing pavement will be evaluated for its potential as a sustainable, realistic alternative material in the upcoming years. The use of diagrams to model the concept will display how rainwater can be diminished by passing through the pavement into the soil, improving stormwater management and groundwater recharge.

The research intention was to determine whether permeable pavement systems serve as an efficient, reliable, and sustainable alternative solution to climate-linked flooding issues in modern urbanized environments, considering current limitations regarding further technology. Different pavement systems (porous asphalt, permeable concrete, permeable interlocking concrete pavers) were compared to determine which mixtures and designs are more efficient and perform better in specific environments, based on several engineering input designs and performance outputs.

Literature Review

In recent years, permeable pavement has become a more popular subject matter as a result of the rise of climate awareness. Many researchers have attempted to enhance this technology and have made various discoveries in their areas of research.

Brattebo and Booth (2003) recognized the issue of stormwater runoff and developed a solution: permeable pavement. This design was made up of a matrix of concrete blocks or a plastic web-type structure with voids filled with sand, gravel, or soil, which allows stormwater to infiltrate into the underlying soil.

Russ Barry (2017) described permeable concrete as a highly porous pavement material composed mainly of large aggregates, allowing for water filtration through the concrete slab, a sustainable technique to reduce runoff.

Mishra et al. (2020) examined how porous asphalt pavements improved sustainability and reduced waste generation by using recycled construction aggregates (RCA) in asphalt mixtures. The report highlighted the dual purpose of porous asphalt pavements: both as a pavement surface and a stormwater filtration system. Using engineering principles, they evaluated the particle shape, durability, water absorption, and strength, concluding that its low-impact technology and long-term environmental benefits serve as a sustainable alternative development for the future.

Santamouris (2013) described permeable asphalt as a bituminous material tied with aggregates, achieving porosity by removing fine particles, producing about 18% void space. Santamouris explained how porous concrete is controlled by factors such as binder type, aggregate selection, compaction, and aggregate grading, with permeability ranging from 20 to 40 mm/s.

Jamshidi et al. (2019) discovered that porous asphalt would be one of the vital permeable pavement technologies, consisting of 20% air voids and permeability of 0.01 cm/s, although the lack of fine materials and clogging and structural failures limit its usage in urban design.

Jiang et al. (2018) reported that the usage of porous asphalt pavements was implemented in Asia and the United States for effective skid resistance and drainage, whereas being utilized for noise reduction in Europe. They said that porous asphalt pavements have been applied worldwide, with designs serving multiple sustainable functions, marking future expansion.

Siwakoti et al. (2023) described permeable-interlocking concrete pavers as efficient systems that provide on-site stormwater management by detaining runoff and removing contaminants. This study combines 376 laboratory experiments to break down PICP systems and address maintenance requirements. Results show that larger pavements are more cost-effective to maintain, with estimated costs of \$0.32/m²/year for 5000 m² areas versus \$0.50/m²/year for 1000 m² areas.

Ceramic Tech Today (2018) developed a new permeable concrete design that consists of recycled carbon fibre composite waste to address both stormwater flooding and industrial waste reuse. These researchers at Washington State University found that adding carbon fibre significantly improved strength and durability while maintaining rapid drainage. This offers a cost-effective and sustainable alternative to traditional flood-control infrastructure. The use of scrap material from aerospace manufacturing reduces landfill waste and shows strong potential for municipal applications.

METHODOLOGY 2

2.1

Water-absorbing roads, known as permeable pavements, are designed as a sustainable road infrastructure alternative, aimed at reducing surface runoff and retaining stormwater to prevent floods. This article conducted a secondary-research approach, relying on credible online sources for data, information, and depictions. Secondary sources were used to make highly efficient and large-scale connections, using high-quality data to test the hypothesis.

The intent is to determine the effectiveness of permeable designs by evaluating engineering designs, such as aggregate size and infiltration rates, including applications and uses of current technology worldwide. Limitations, containing frequent maintenance, helped weigh out whether or not permeable alternatives should be sought within urban environments. Data amongst systems were divided into input design variables (Aggregate Size, Water/Cement (W/C) Ratio, Layer Thickness, Recycled Materials) and performance variables (Infiltration Rate, Porosity, Compressive Strength, Durability) to get precise samples of each.

2.2

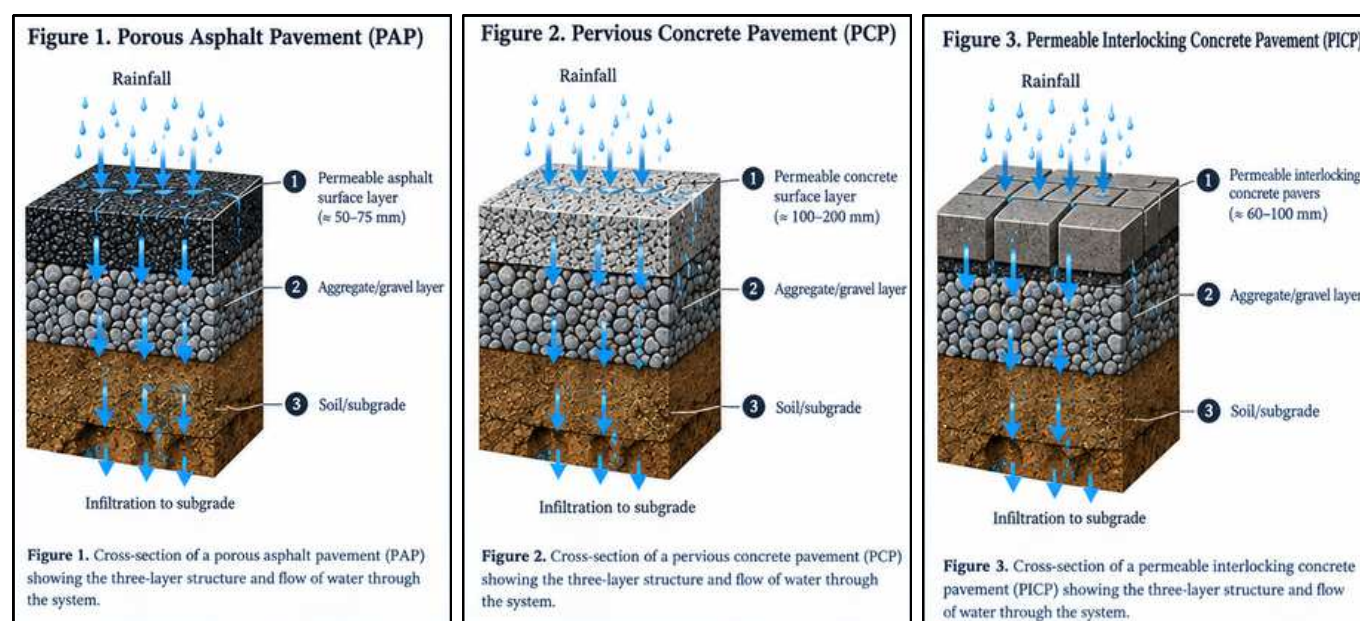
Data were collected from peer-reviewed research journals, government agencies, permeable pavement companies, academic organizations, and environmental and engineering databases. In these sites, keywords such as “porous pavement (asphalt/concrete)”, “permeable pavement(asphalt/concrete)”, “sustainable drainage systems”, “environmentally efficient infrastructure”, “stormwater control”, and “permeable interlocking concrete pavements ” were used. These consisted of material properties, climate considerations, cost analysis, rainfall statistics, and real-life examples of permeable concrete being used. Main databases stemmed from SCIEDIRECT, where many credible case studies and other published works were available and selected to explore environmental and science topics. Sources ranged from 1999 to 2025 in publication date, exploring data and changes among permeable technologies, spanning 26 years of studies. They provided quantitative data, consisting of permeability, infiltration rates, cost estimates, porosity, and environmental risk factors. For the validity of information, governmental reports and peer-reviewed studies were given priority when accounting for the credibility of sources because they undergo rigorous review processes. Samples were collected from various geographic locations worldwide (incl. North America and Asia), representing the performance of porous products in different climates.

2.3

Collective data were analyzed using comparative evaluation. These studies were compared to find similarities of 3 core permeable systems (porous concrete, porous asphalt, permeable interlocking concrete paver systems), standard uses, engineering design, estimated prices, common materials, and limitations of the technology to determine value as a long-term innovation. These pavement variants were then contrasted in an in-depth chart analysis to determine benefits and drawbacks. Comparisons were made by determining rough estimates of significant engineering factors of different systems through mutual findings. They then analyzed and evaluated which traits of each would perform and thrive best in certain locations and climates, ultimately determining permeable system viability as a long-term, sustainable technological alternative. Cost-benefit metrics were vital in comparison, due to the focus on opportunity costs of valuing certain principles, such as porosity (%) over compressive strength (MPa) and vice versa.

2.4

Small-scale diagrams, shown in Figures 1, 2 and 3, are constructed to communicate the visual functionality of permeable pavements and compare the various systems (PAP, PCP, PICP). This includes a permeable surface layer (see #1 in Figures 1- 3), an aggregate/gravel layer (see #2 in Figures 1- 3), and a soil/sand layer below the pavement (see #3 in Figures 1-3).



In these models, an immense rainfall scenario was simulated to examine the infiltration efficiency of the design, observe drainage patterns, and assess the reduction in surface pooling. The results supported the literature by showing how porous pavement reduces runoff and prevents flooding.

Diagrams were incorporated to illustrate pavement structures, porosity ratios, layer thickness, differences in impermeable and permeable systems, infiltration rates, and other engineering components. These diagrams were utilized to enhance understanding of real-world permeable systems and further represent the similarities and disparities between different permeable system designs. The intent was to recap and simplify all key findings, providing a brief sample of data and repeated patterns depicted through research. Each model represented characteristics of distinct systems used in research, obtaining approximate calculations of performance efficiency and efficacy.

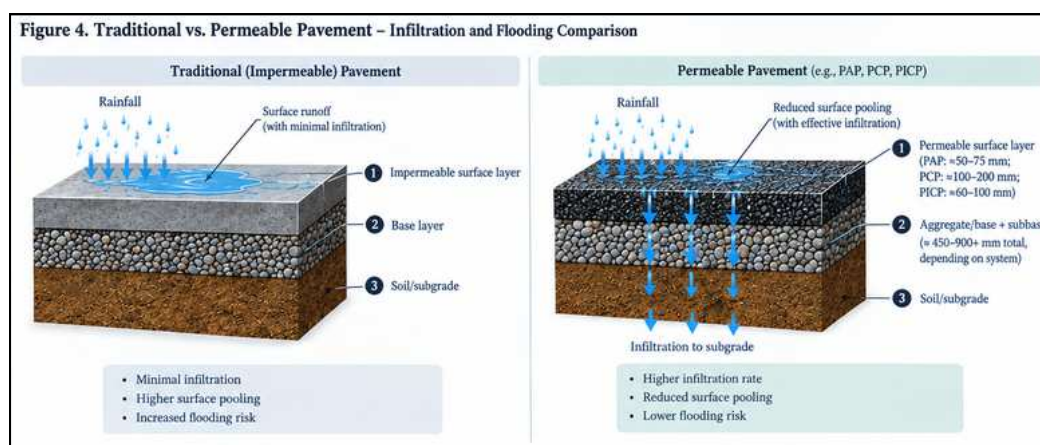


Figure 4 mocked the concept of traditional pavement designs (minimal infiltration), examining the limitations in water absorption and flooding risk. When flooding simulations were conducted alongside a traditional concrete model, the range of effectiveness in porous structures was more evident, in which remaining surface water and infiltration rate were closely compared.

2.5

In this research paper, the limitations consisted of:

- Reliance on existing literature and data from secondary sources
- Small-scale modelling diagrams showing basic visual comparison
- No laboratory experimentation or monitoring of large-scale permeable pavement installations
- Economic analysis based on estimated costs, subject to area, material availability, and installation scale

Results and conclusions were dependent on precise estimates of published research and existing discoveries, which may not replicate the real-world performance of permeable products to absolute certainty and accuracy.

RESULTS AND FINDINGS 3

Pavement type	Porous Concrete System
Aggregate Size	Single-sized coarse aggregate: 4.75–20 mm (optimal <10 mm for strength)
Water/Concrete Ratio	Typical: 0.30–0.40 Optimal: 0.30–0.35
Porosity (%)	Typical: 15–25% Optimal balance: ~20%
Compressive Strength (MPa)	Typical: 5–20 MPa Optimized: up to ~25 MPa (max reported ≈ 40+ MPa with additives)
Infiltration Rate (in/hr)	Typical: 300–3,000 in/hr (very high when unclogged)
Durability Attributes	Lower than conventional concrete; improved with fibers, silica fume, polymers
Recycled Materials	Recycled aggregate, fly ash, slag, silica fume, pumice
Layer Thickness (mm)	Surface: 100–200 mm; Base + subbase total: 450–900 mm
Limitations (Maintenance)	Susceptible to clogging & freeze–thaw damage; vacuum cleaning required
Estimated Cost (\$\$)	~\$2–10 USD/ft² (≈ 25% higher than conventional concrete)
Common Uses	Parking lots, sidewalks, low-traffic roads, walkways
Key Benefits	Extreme infiltration, groundwater recharge, heat island reduction

Pavement type	Permeable Interlocking Concrete Pavers System (PICP)
Aggregate Size	Joint fill: 2.36–4.75 mm (ASTM No. 8 / 9) Bedding layer: 2.36–9.5 mm (ASTM No. 8) Base layer: 13–25 mm (ASTM No. 57) Subbase layer : 50–75 mm (ASTM No. 2–4)
Water/Concrete Ratio	Not Applicable (precast concrete units)
Porosity (%)	Pavers not porous; effective open area: around 5–15% (Turfstone up to 40%)
Compressive Strength (MPa)	Pavers: 35–60 MPa (much higher than PA & PC)
Infiltration Rate (in/hr)	Initial: 100–1,000+ in/hr Long-term design: ~10–25 in/hr
Durability Attributes	Excellent freeze–thaw resistance; 40–50+ year service life
Recycled Materials	Fly ash, slag; pavers fully recyclable at end of life
Layer Thickness	Pavers: 60–100 mm; Base + subbase: 450–900+ mm
Limitations (Maintenance)	Joint clogging; vacuum sweeping required; sand discouraged
Estimated Cost (\$\$)	~\$5–10+ USD/ft² (higher upfront, lower life-cycle cost)
Common Uses	Parking lots, driveways, plazas, low-speed roads
Key Benefits	Highest strength, repairable, long life, strong stormwater control

Pavement type	Porous Asphalt System
Aggregate Size	9.5–19 mm open-graded aggregate, minimal fines
Water/Concrete Ratio	Asphalt binder content ≈ 6–7% by weight
Porosity (%)	~15–25% air voids (design range 16–22%)
Compressive Strength (MPa)	2.8 to 28 MPa (400 to 4,000 psi)
Infiltration Rate (in/hr)	New: 200–1,000 in/hr Design: ~12–72 in/hr
Durability Attributes	18–30 year lifespan with maintenance; polymer-modified binders improve durability
Recycled Materials	Can include recycled asphalt pavement (RAP), polymer additives, plastic waste
Layer Thickness (mm)	Surface: 50–75 mm (2–3 in); Total system incl. base: 450–900 mm
Limitations (Maintenance)	Surface clogging; vacuum sweeping 2–4× per year; avoid sand in winter
Estimated Cost (\$\$)	~\$5–9 USD/ft² (10–20% higher than conventional asphalt)
Common Uses	Parking lots, low-speed streets, trails, alleys
Key Benefits	High infiltration, reduced runoff, noise reduction, groundwater recharge

An immense number of studies were compiled to get rigorous approximations of the engineering principles of the 3 core permeable pavement systems: porous asphalt, permeable concrete, and permeable interlocking concrete pavers. These data included input design variables (Aggregate Size, Water/Cement (W/C) Ratio, Layer Thickness, Recycled Materials) and performance variables (Infiltration Rate, Porosity, Compressive Strength, Durability) to measure the effectiveness of different systems. Similar trade-offs were also considered that linearly affect the production of systems and the cost-benefit shift that occurs when these decisions are made.

3.1

The information collected from the studies shows that the material used and the way it is structured in pavement can greatly influence how well the pavement works. For the types of surfaces studied, when there is more porosity, there is usually more space for water to move through, which helps water get into the ground. For asphalt, having about 20% air space has been linked with permeability levels of around 0.4 to 0.5 cm/s. The top layer of this pavement is usually 40 to 50 mm thick for one layer or 70 to 100 mm thick for two layers (Jiang et al. 2018). Big and open structures made from stones can also add space for water to flow through. However, spaces can make the pavement worse at carrying heavy weights.

Water-to-cement ratios are very important for concrete. If the water-to-cement ratio is low, the cement becomes stronger. If it is too low, there might not be water to cover and bind the stones properly. If there is too much water, the cement mixture can move into the open areas, which reduces the amount of connected spaces and makes the pavement less permeable. So the relationship is not that lower water-to-cement ratios always mean better pavement. An appropriate ratio is needed to make sure the pavement is strong and also allows water to pass through. For the thickness of the structure, permeable interlocking systems include blocks that fit together, materials in the joints, materials under the blocks and a base and subbase. The blocks and base layers help spread the weight of vehicles, while the open parts between the materials let water move through (Jamshidi et al. 2019).

Overall, the results show that there is a trade-off between making space for water to enter and keeping enough strength for the pavement to handle traffic. It is clear that pavements with spaces are usually better at letting water pass through, but denser structures are better at handling heavy weight. So when designing pavement, the size of the stones, the water-to-cement ratio, the porosity and the layer thickness cannot be chosen alone. They all have to be considered

3.2

The strength and how long the pavement lasts are mainly based on the strength of the materials in the layers of the structure, how the stones are held together, and how well the pavement holds up over time. One of the things seen in the data is that there is a trade-off between the amount of space and the strength of the structure. Increasing the number of spaces helps water pass through. It also reduces the amount of solid material that can carry the weight. So porous systems are better for places where there is no traffic, while systems that need more strength have to be designed to control how much open space they have.

Permeable interlocking systems were found to last a long time in real-life tests. Brattebo and Booth (2003) looked at four types of pavement after six years of use and found that none of them had much damage. The Turfstone and UNI Eco-Stone systems did not show any signs of sinking, moving or getting flat. They were as good as asphalt in the conditions studied. So it seems that permeable pavement can continue to work for years. However, the study also found that some flexible plastic systems shifted slightly, which shows that different types of pavement can react differently to repeated weight.

For concrete-based systems, the strength has been found to be linked to the amount of porosity and how the mix is made. A pavement with porosity allows a lot of water to pass through but may not be strong enough for heavy vehicles. If the spaces are smaller, the strength goes up. The amount of space for water to move through goes down. So the best system depends on what it's used for. Stronger systems are better for places with lots of cars, while permeable systems are better for parking lots, sidewalks and other places with traffic. Overall, the results show that the best pavement is not always the strongest or the most permeable, but the one that has a balance between these two things.

3.3

The results related to water show that permeable pavement can greatly reduce the amount of water that flows over the surface by letting rainwater go through the pavement and into the ground. Brattebo and Booth (2003) found that all the rainwater went through the four types of pavement tested in a parking area after six years of daily use, meaning very little water ran off the surface. This shows that permeable pavement can keep working and help manage stormwater for years.

Similar results were found in soil conditions. Dreelin et al. (2006) compared a parking lot with pavement to one with asphalt on soil that had a lot of clay. The porous pavement had 93% less runoff than the asphalt one during the rain events studied. Water also moved into the ground in most of the storms. The permeable pavement helped reduce runoff in places where the soil did not let water get in easily. However, the results still depended on the soil and how hard it rained.

The amount of porosity was important in deciding how well the system let water pass through. More open spaces gave ways for water to move through. Too much porosity could make the pavement weaker. So the systems that took in the water were not always the choice for a certain place. The findings show that permeable pavement can be very good at reducing runoff from parking lots, sidewalks, driveways and other places with high traffic because the benefits of managing water can be achieved without needing the strength of major roads. Overall, the results support using pavement as a way to help rainwater move through built-up areas naturally.

3.4

Recycled materials that permeable asphalt pavement systems can contain include acrylonitrile styrene acrylate (ASA), plastic waste, recycled construction aggregates (RCA), and asphalt mixtures (Mishra et al.). ASA has proven to have 6-10x higher permeability than conventional asphalt, serving as a very efficient, environmentally friendly material (Sousa et al.). RCA has produced satisfactory results in stability and permeability values when mixed with permeable asphalt pavements (PAP), being utilized in PAP development (Nejem and Akhtar). Samples by Hardiman proved that when PAP systems are mixed with natural coarse aggregates (NCA), satisfactory stability and permeability values are produced. The immense impact of environmental conditions on PAP permeability was highlighted in a small-scale sample where a permeability of almost 4000×10^{-6} m/s decreased to 2500×10^{-6} m/s over a year. Asphalt-coated recycled aggregates (50% fill) may result in reduced bonding and slight strength reduction. These benefits contain reduction of landfill waste and natural aggregate mining, thus improving

efficiency (Hassan et al. 2021). Additionally, Porous asphalt decreases pollution risk by dispersing stormwater (Palmer and Ap). The infiltration rate and the storage capacity are both above the design values. They contribute to increased water quality by filtering pollutants, reducing spray, hydroplaning and tire noise. Effectively, asphalt models can retain up to 93% of suspended pollutants long-term, infiltrating stormwater and reducing flooding (Sousa et al.). Other ecological benefits of PAP systems include reducing urban waterlogging and aiding in groundwater replenishment, essential for environmental sustainability. The incorporation of recycled coarse aggregates from waste-tested laboratory samples preserves resources and minimizes waste, providing enhanced water flow capacity and significant durability (Nejem and Akhtar).

Porous concrete systems (PCP) can be constructed from (non-toxic) recycled ceramic tiles, mineral powder, silica fume, and natural aggregates (Hermann, Zhang et al.). These systems can improve compressive strength and durability, but not all pozzolanic materials are effective (Sánchez-Mendieta et al.). These recycled aggregate concrete systems converge with international specifications, achieving acceptable mechanical and hydraulic performance while reducing pollution (Hassan et al. 2021). According to numerous case studies, PCP systems often show 99-100% volume retention in stormwater reduction and remove around 85-95% of pollutants (WisDOT). Improved bending capacity, increased traffic resistance, and enhanced mechanical response can be achieved by integrating 0.1% content Polypropylene (additive optimal) fibre (Reyad et al.). This recycled alternative provides a more efficient performance than conventional concrete pavements. Another vital option consists of natural volcanic pumice aggregates, producing lightweight, high-porosity, and reduced material density. Although not recycled, the materials are eco-friendly and natural, ensuring long-term reduced resource consumption and sustainable construction materials (Das and Deepak Kumar Juneja).

In permeable interlocking concrete paver (PICP) systems, recyclable concrete substitutes include fly ash, slag, and silica fume. Pavers by Ideal states that the absence of petroleum-based materials allows PICP to be crushed and recycled after end-of-life. PICP contains all-natural materials, which include cement, sand, stone, iron oxide pigments and water. This is accompanied by its strong pavement base durability, unlike PAP and PCP systems that use monolithic materials. PICP units do not crack, have easy utility repair systems, and do not leave visible patches where reinstated (UNILOCK). Oil spills from moving material absorb or biodegrade safely over time, enhancing environmental protection. Its suitable environmental benefits, withstanding urban and industrial traffic, make PICP systems the best alternative for environmental sustainability and pollutant removal (Nejem and Akhtar, Drake and Banting, Moretti et al.).

3.5

Significant drawbacks of permeable technology include limitations and maintenance requirements that require in-depth consideration when accounting for long-term reliability and sustainability of systems. PAP models can cause pollution of groundwater due to oil spills and other toxic leakages, extending into soils (Palmer and Ap). Clogging remains the central issue of these permeable structures, resulting from asphalt draining down from the surface and settling lower in the asphalt pavement (Sousa et al., Palmer and Ap). The use of polymer-modified asphalt, stiffer asphalts and sometimes fibres mitigates this effect. There is also a required quarterly (3-4x annually) vacuum-sweeping for removing fines (debris from pores) to maintain permeability and prevent blockage (Kathale et al., Nejem and Akhtar). If clogged, these systems can become very difficult to restore, and the repaired area may

not match the surrounding surface. Moreover, there has to be periodic pressure washing to clean deeper contaminants. Winter climates may freeze saturation, possibly damaging concrete. For this reason, PAP systems cannot be installed during winter and require a 7-day cure prior to traffic. If not followed, lifetime performance will be at risk, and more frequent labour will be needed. PAP systems are commonly utilized in good products for local roads, sidewalks, alleys, parking lots and trails (Palmer and Ap, Sousa et al.). They are designed for poor subgrade, but soft, yielding subgrade could be a concern (Palmer and Ap).

PCP models require vacuum sweeping and deicing salt management (only in moderation). They are also more susceptible to clogging and freeze-thaw scaling damage than PAP systems, containing less strength than conventional concrete when improperly installed (Nejem and Akhtar, Ibrahim et al.). If the surface is not kept clean, clogging is a very possible risk that can appear (Mr. Gaurav Uttam Shinde and Dr. S. S. Valunjkar). WisDOT Research & Library Unit studies indicate that clogging can also reduce infiltration from 100s of inches per hour to an estimated 5 in/hr, emphasizing frequent maintenance when installed. Additionally, its lower strength than conventional concrete makes models sensitive to porosity level, aggregate size and shape, paste thickness, mix compaction, and permeability, which all need to be carefully considered and balanced when forming mixtures (Zhang et al., Sánchez-Mendieta et al., Hassan et al.). The sensitivity of PCP strength is dependent on the compaction and mix design (Mr. Gaurav Uttam Shinde and Dr. S. S. Valunjkar). This requires careful optimization of pumice percentage and control of void content to prevent poor aggregations, which can cause strength deviations up to 45% (Zhang et al.). Recycled aggregates may also reduce bonding due to the asphalt coating. Wear resistance and freeze-thaw also require further research, limiting PCP to only low-traffic roads (Ramadhan et al.). Due to several limitations, some sites may still need supplemental surface drainage near buildings (Hermann). For these reasons, PCP systems are commonly utilized in parking lots, walkways, plazas, driveways, residential (low volume) streets, or uncrowded urban areas with severe flood risk to reduce runoff and improve water quality (Reyad et al., Das and Deepak Kumar Juneja, Mr. Gaurav Uttam Shinde and Dr. S. S. Valunjkar, Hermann, Zhang et al., Ramadhan et al., Kathale et al., Sánchez-Mendieta et al.).

Similarly, PICP systems are not ideal alternatives for very heavy traffic, with common clogging occurrences in joint material due to a lack of maintenance (Drake and Banting, WisDOT). UNILOCK describes primary maintenance concerns that include sediment and debris accumulation, reducing infiltration, routine surface cleaning essential to maintain performance, clogging by fine sediment, and restorative repairs involving paver removal and resetting systems. Due to joint material and surface clogging, vacuum sweeping (3-4x annually) is highly recommended (WisDOT, IDEAL). Factors of performance are determinant on joint material, joint width, pavement slope, bedding layers, and winter storm and ice management to avoid clogged voids from sand (Drake and Banting). Therefore, hydraulic design must consider both vertical infiltration into base/subgrade and horizontal bypass flows across the surface (Kevern et al.). Routine sweeping maintenance and long-term planning will preserve infiltration capacity and extend service life (UNILOCK), but if ignored, can decrease infiltration over time. This produces a higher risk of hydrocarbons & heavy metals (Moretti et al.). Case studies also reveal that high stormwater volume retention (34-100%) is contained in PICP models, but are determinant on structural production. Using a laboratory rainfall simulator, Hashim experimented with PICP performance by testing rainfall conditions with intensities of 20 L/min, 40 L/min, and 60 L/min. He concluded that performance decrease can result from high rainfall and steep slopes, making a balance between hydraulic performance and structural capacity

vital (Hashim et al.). Systems are not suitable for heavy truck traffic and roads with high speeds over 50 km/h (35 mph) (FHWA). PICP systems are also required to avoid high sediment loads and hazardous material loading environments, rather than being utilized in parking lots, plazas, driveways, low-speed roads, green alley projects, and similar paved areas (WisDOT, FHWA).

3.6

Due to easy repair, cost limitations of PICP models include higher upfront costs, high initial construction costs, and a need for operations/maintenance staff training to maintain benefits for the long term. For this reason, permeable system installation may spark hesitation, but it is important to note that PICP systems are expected to have lower total life-cycle costs than conventional asphalt pavements (ARA, FHWA). They also have reduced stormwater infrastructure, pollutant, and sewer overflow costs, supporting sustainability and eco-friendly infrastructure decision-making (ARA). TSR reports estimated costs ranged from \$2-8 USD/ft² for PICP systems on the EPA pavers page (WisDOT). Calculations done by Applied Research Associates Inc. (ARA) estimate life-cycle cost savings of approximately \$4.25M over traditional asphalt in a modelled community case (ARA). Additionally, per-area costs of PICP construction are typically around \$4.9-5.8 USD/ft², with rehabilitation of \$2.73-2.77 USD/ft², and maintenance of \$0.05-0.10 USD/ft²/yr (NPV). Over a 50-year sample period, PICP may have a higher initial cost but a much lower total life-cycle cost than conventional pavements with catch basins and pipes when stormwater and maintenance savings are included, accounting for reduced needs for storm drains, detention ponds, and underground piping (IDEAL, ARA). PICP are cost competitive with porous asphalt and pervious concrete, having a typical installation cost range between \$5-10 USD/ft² for units. They have the lowest life-cycle costs amongst all the current existing permeable technologies (IDEAL).

PCP also has expectedly lower costs than traditional drainage systems (Zhang et al.). Their initial costs are roughly 25% higher than regular concrete pavements, but ultimately result in lower life-cycle costs than conventional pavements with catch basins & pipes (IDEAL, Mr. Gaurav Uttam Shinde and Dr. S. S. Valunjkar, Ibrahim et al.). The TSR data in 2005 differs slightly, mentioning that material/construction cost can range from \$2-7 USD/ft² (2005 dollars), being generally 10-20% higher than non-permeable materials (WisDOT, Ibrahim et al.). However, this price can be offset by reduced demand for detention basins and other stormwater infrastructure. In 2021, typical estimated installation costs ranged from \$8-12 USD/ft² depending on variants of aggregate and model mixtures in design (Hassan et al.). Due to inflation of separate material costs, these prices can be expected to rise by 15-30%, depending on the company, location, and model construction.

US national averages indicate that PAP systems can cost around \$5-9 USD/ft² (2025), being significantly more costly since 2005, when the material cost was \$0.5-1.0 USD/ft² (WisDOT). PAP is reported to be 10-20% more expensive than standard asphalt but offset by the removal of detention basins, with estimated costs of \$2000-2500 USD (per parking space) (Palmer et al.). A Study on a PAP installation project in the city of Puyallup, 8th Ave NW, was conducted by Palmer in 2014. He approximated \$8.98 USD/ft² for the cost of the top 2 layers (asphalt and binder/levelling course), with overall costs (incl. all city installations on the project) of \$23.49 USD/ft², estimated to be an even higher expense at present. Although the project had a total cost of \$431,700 USD, it was evaluated to be about \$100,000 USD cheaper than a traditional road project would have been. As shown, PAP systems can be

very credible and involve substantial long-term total savings, making system implementations progressively beneficial throughout lifespans.

Discussion and Conclusions 4

4.0

The findings support the hypothesis that permeable pavement is a viable alternative to conventional impermeable paving systems because it combines the functions of both pavement and storm drainage. The function of permeable pavement can be attributed to the compromise made between permeability, structural integrity, durability, environmental impact, maintainability, and cost. Therefore, an effective evaluation of permeable pavement function should incorporate how a system performs overall to address site needs rather than on the system's attributes.

It should be noted that each of the three studied permeable pavement systems have their own distinct strengths and weaknesses that apply differently depending on each application. For applications that need a high rate of infiltration, porous asphalt pavement (PAP) should be considered due to it using an existing, accepted form of asphalt. Permeable concrete pavement (PCP) can also be a viable alternative if the right mixture proportions are chosen since an optimum balance between water infiltration and strength can be achieved. Although PICP can have excellent stormwater benefits, it generally has higher costs and difficulty in repairs.

All three pavement systems have strengths, but no system excels at all potential required functions, so it is imperative to understand your application and site demands, from rainfall amount to traffic and soil conditions. In regard to the environmental benefits of permeable pavement, its ability to infiltrate rainfall in situ, thereby reducing the pressure on urban drainage systems and flooding, clearly positions it as a desirable pavement option. In addition, certain types of permeable pavement allow the utilization of recycled materials within them, further lessening demand on virgin materials. Even though many environmental benefits exist for permeable pavement, the adverse environmental effects of its constituent materials, such as cement and asphalt, must be balanced and considered in addition to an application's suitability, and hence 'permeable' should not simply be assumed positive until a life cycle assessment is performed.

One of the largest factors in the effectiveness of permeable pavement over a long period of time is maintenance. The silt, sand, and gravel that collect over the lifetime of the pavement within its pore spaces hinder hydraulic function, thus necessitating routine inspections and cleanings, which makes permeable pavement not a 'maintenance-free' system (Siwakoti et al., 2023). It is also important to consider the high initial cost of installing permeable pavement and how its long-term benefits, such as improved stormwater management and lessened strain on infrastructure, will balance this expense through future avoidance of disaster recovery.

Many studies have noted an inability to reach desired results after the construction of permeable pavement; the performance can be affected by a myriad of things, including soil conditions, amount of rain received, traffic volume, quality of construction, and climate. Cold climates can cause difficulties with freeze/thaw and winter maintenance, while sites with high silt loads may need more frequent clogging inspections. Because these vary so much by region, it is important to conduct the proper site analysis before choosing and investing in a permeable pavement application and ensure that both your climate and soil type can accommodate the proposed permeable system.

Compared to impermeable systems, permeable pavements possess added benefits with respect to on-site stormwater infiltration and management, but are they a feasible alternative to typical pavement types? Whereas conventional asphalt/concrete pavement may remain better for high-volume traffic/load areas requiring extensive structural support, the improved infiltration in suitable areas has clear advantages as opposed to the negative stormwater effects traditional pavement imparts on the local area. Therefore, applications such as driveways, parking lots, walkways, residential areas and roads with very light traffic volume can likely find permeable pavement as a more efficient and more advantageous pavement type application over traditional asphalt/concrete pavement. So, while a complete transition may be impractical throughout an entire municipality, application at suitable locations like the ones mentioned may offer a beneficial stormwater solution.

In conclusion, the presented evidence supports the premise that the appropriate design and maintenance of a permeable pavement can lead to a functional stormwater management system and approach throughout the long term, but a successful stormwater plan requiring permeable pavement must be specifically designed to accommodate certain conditions of installation and local climates. The various pavement systems, PAP, PCP, and PICP, each contain strengths and weaknesses, and no single system will serve as an application at every site, making pavement selection specific to demands rather than a classifiable solution. Thus, local municipalities should consider permeable pavement systems as an integral part of their stormwater management infrastructure that can provide immense stormwater benefits with appropriate engineering design for site-specific needs. The study should be expanded with long-term performance testing based on climate and soil types, research the optimal maintenance and anti-clogging techniques for permeable pavement, and provide a comprehensive comparative life cycle analysis comparing various pavement types and stormwater management strategies.

Recommendations 5

5.0

In urban areas, permeable pavement is most appropriate in applications where some measure of stormwater infiltration may be beneficial and structural loads are moderate (e.g. parking lots, sidewalks, residential driveways, and low-volume roads), but only when site conditions (soil options, climate options, drainage options, traffic options) will allow for a hydro-modification to the hard surface. Municipalities would be a major consumer of waste based on engineering design and ongoing maintenance; the research should include investigations into long-term field performance, future clogging mitigation, and life-cycle analysis for multiple climatic and soil scenarios.

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