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PERVIOUS CONCRETE AS A MULTIFUNCTIONAL SOLUTION FOR SUSTAINABLE URBAN STORMWATER MANAGEMENT

Abstract:

Intensive urbanization increases impervious cover, accelerates stormwater runoff, and aggravates flooding, water pollution, and urban heat island effects. This paper provides a critical narrative review of pervious concrete as a multifunctional material for sustainable stormwater management. The review synthesizes studies on hydraulic performance, pollutant removal, clogging, durability, maintenance, and broader environmental co-benefits of pervious concrete. The analyzed literature indicates that pervious concrete can effectively reduce runoff and improve water quality, but its performance strongly depends on mixture design, construction quality, and maintenance. The main limitations are clogging, sensitivity to freeze–thaw conditions, and insufficient long-term field data.

Keywords: pervious concrete, stormwater management, infiltration, urban heat island, sustainability

ВОДОПРОПУСНИ БЕТОН КАО МУЛТИФУНКЦИОНАЛНО РЕШЕЊЕ ЗА ОДРЖИВО УРБАНО УПРАВЉАЊЕ АТМОСФЕРСКИМ ВОДАМА

Сажетак:

Интензивна урбанизација повећава удео водонепропусних површина, убрзава отицање и појачава ризик од локалних поплава, загађења вода и ефекта урбаног топлотног острва. Рад даје критички наративни преглед водопропусног бетона као мултифункционалног материјала за одрживо управљање атмосферским водама. Сагледани су радови о хидрауличким својствима, уклањању загађујућих материја, зачепљењу, трајности, одржавању и еколошким бенефитима. Литература показује да водопропусни бетон може смањити отицај и унапредити квалитет воде, али да његове перформансе зависе од састава, извођења и одржавања.

Кључне речи: водопропусни бетон, управљање атмосферским водама, инфилтрација, топлотно острво, одрживост

1. INTRODUCTION

Contemporary urban development is characterized by the expansion of impervious surfaces such as asphalt and conventional concrete, which substantially reduces infiltration into the soil and increases stormwater runoff volume and peak flow [1], [2], [3]. The consequences include more frequent local flooding, overloading of drainage systems, and contamination of receiving waters, all of which are further aggravated by climate change and more frequent hydrologic extremes. Within this context, sustainable urban drainage systems (SUDS), low-impact development (LID), and related blue-green infrastructure concepts have become increasingly important because they seek to restore part of the natural hydrologic response in urban areas [4], [5].

Within these approaches, pervious concrete (PC) represents one of the key technical solutions. Unlike conventional concrete, PC contains little or no fine aggregate and is characterized by a high proportion of interconnected voids, typically in the range of 15% to 30% [6]. This structure allows direct infiltration of stormwater into the underlying layers, thereby reducing runoff volume and relieving the urban drainage system [7], [8]. At the same time, properly designed systems can contribute to water-quality improvement and partial restoration of the local water balance [9], [10].

In addition to its hydrologic function, the literature increasingly emphasizes the multifunctional character of PC. Studies indicate its potential for retaining suspended solids and some pollutants, mitigating urban heat island effects through evaporative cooling, and providing certain acoustic benefits [11], [12], [13]. However, these advantages are not automatic, because performance depends on mixture composition, construction procedures, loading conditions, and maintenance during service life [7], [8], [9], [10], [11], [12], [13], [14].

At the same time, several open questions remain. The long-term performance of PC is primarily threatened by pore clogging, while freeze–thaw exposure and the variability of field performance further complicate its application [15], [16], [17]. Therefore, studies that connect degradation mechanisms, maintenance strategies, and life-cycle considerations are becoming increasingly important, because only such an integrated approach can support a more reliable assessment of the actual sustainability of pervious pavement systems [18], [19].

Although many papers address the hydraulic and material properties of pervious concrete, fewer review-oriented studies simultaneously synthesize its role in stormwater management, its effect on water quality, durability issues, maintenance requirements, and broader sustainability co-benefits. The research gap is therefore not a lack of isolated findings, but a lack of sufficiently integrated interpretation of these findings within the framework of green infrastructure and climate adaptation.

The aim of this paper is to provide, on the basis of critically reviewed literature, an integrated overview of the key hydraulic properties of pervious concrete, its environmental functions, application limitations, and its potential for broader integration into sustainable urban water systems. Particular attention is devoted to the relationship between infiltration performance, pollutant removal, clogging, maintenance, durability, and multifunctional urban-environmental benefits.

2. RESEARCH METHODOLOGY AND CLASSIFICATION OF REVIEWED STUDIES

This paper is structured as a narrative review with a critical discussion of studies dealing with the hydraulic behavior, water-quality effects, durability, maintenance, and multifunctional performance of pervious concrete. The review is based on publications most frequently cited in the current body of work on pervious pavements, with emphasis on journal articles, technical reports, conference contributions, and authoritative guidance documents that are relevant to urban stormwater management, pavement engineering, and sustainable infrastructure.

The reviewed works were classified according to their dominant research theme. The first group comprises studies on hydraulic and material properties, including porosity, infiltration, and the influence of mixture composition and compaction [6], [7], [8], [14]. The second group includes studies focused on water quality, pollutant retention, and stormwater treatment mechanisms [9], [10], [11], [20].

The third group covers studies on durability, clogging, and maintenance, including laboratory investigations, CT-based characterization, and numerical modeling of degradation and cleaning processes [15], [16], [17], [21]. The fourth group includes studies on multifunctionality and sustainability, such as thermal behavior, acoustic effects, life-cycle considerations, and the use of recycled or low-carbon constituents [12], [13], [18], [19], [22], [23].

The review approach is qualitative rather than meta-analytic. Instead of statistically pooling data, the paper compares research directions, identifies recurring findings, and highlights inconsistencies and unresolved issues. This approach is suitable because the available studies differ substantially in experimental conditions, environmental exposure, material design, and performance indicators.

3. BASIC HYDRAULIC PROPERTIES AND STORMWATER MANAGEMENT

The defining characteristic of pervious concrete is its ability to achieve infiltration rates that are not possible with conventional impermeable pavements. High permeability is enabled by the large volume of interconnected pores created by the absence or reduction of fine aggregate and by the careful control of paste content [6], [14]. In practical terms, this property allows rainfall to pass through the pavement surface and either infiltrate into the subgrade or be temporarily stored within the base and subbase layers [7], [8].

The effectiveness of PC in stormwater management lies in its ability to reduce both the runoff volume and the peak discharge. According to the reviewed studies, permeable pavement systems can help mitigate local flooding, support partial groundwater recharge, and reduce the burden on conventional drainage infrastructure, especially where decentralized stormwater control is required [3], [4], [8], [24].

In addition to direct infiltration, innovative water-retaining pavement systems (Fig. 1) use the pore space of PC together with filler materials of higher water-holding capacity. These fillers store water temporarily and release it gradually through evaporation and infiltration, thereby extending the hydrologic and thermal functions of the pavement system [3].

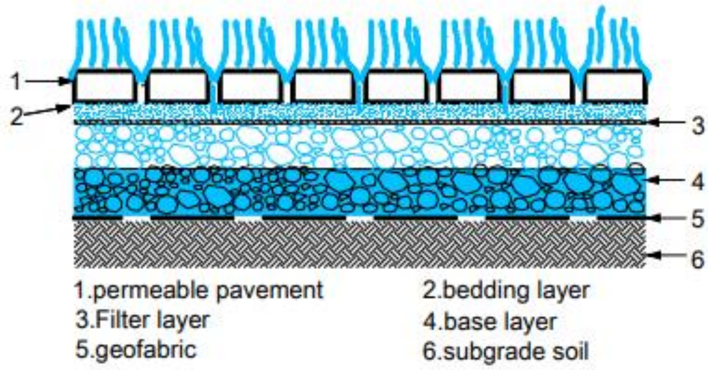

Figure 1. Schematic application of a water-retaining pavement system for stormwater storage and infiltration [3].

Although mixture design determines the potential porosity of the material, actual hydraulic performance depends strongly on compaction during construction. Several studies have shown that the degree of compaction has a direct, generally inverse influence on permeability. Greater compaction can improve compressive strength but simultaneously reduce hydraulic conductivity and pore volume [7], [14].

A critical finding is that excessive compaction can noticeably reduce permeability for a given mixture [7]. Even more importantly, excessive vibration may lead to denser lower layers within the slab and to the formation of hydraulic discontinuities through the pavement thickness [25]. Consequently, PC engineering must go beyond mixture proportioning alone. Quantitative field control of compaction is necessary to achieve more uniform, design-level porosity throughout the pavement depth, particularly in thicker installations.

4. ENVIRONMENTAL FUNCTION OF PERVIOUS CONCRETE

Pervious concrete can function as an effective geochemical filter for stormwater. The primary mechanisms of water-quality improvement include physical filtration of suspended solids as well as chemical interactions promoted by the alkaline cementitious matrix. As runoff passes through the porous system, particulates can be retained within the pore network, while some dissolved contaminants may be immobilized or transformed [9], [10], [11]. The distribution of measured water-quality parameters across all sample types and storm events is illustrated in Fig. 2.

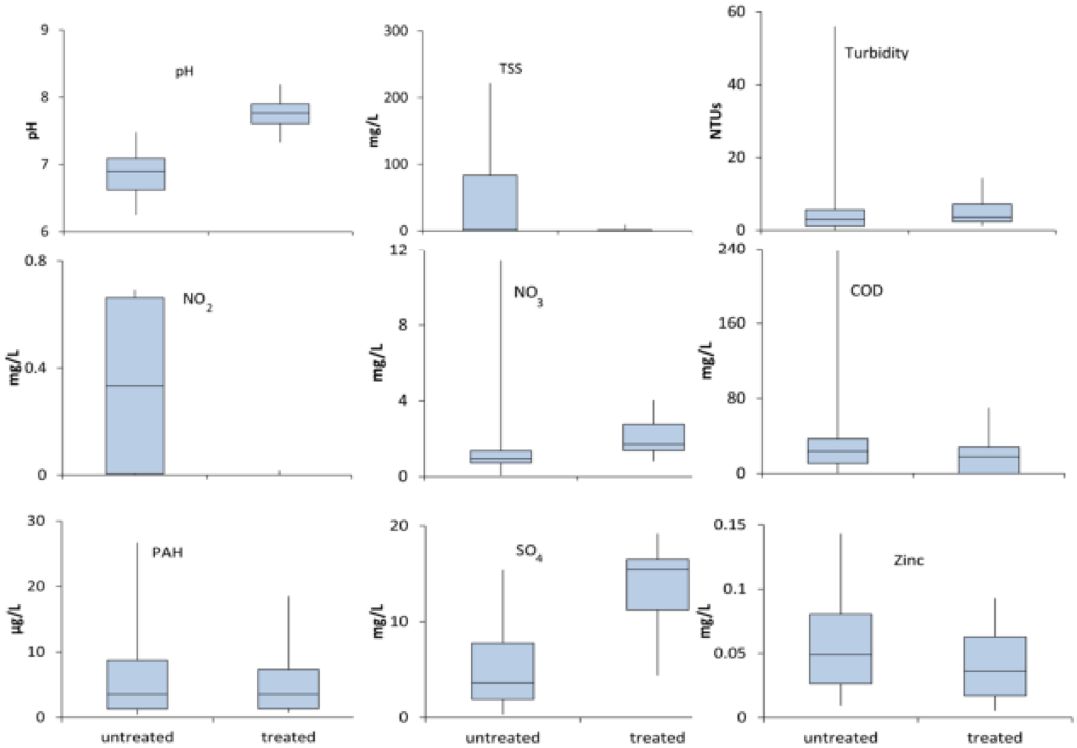

Figure 2. Diagrams of nine types of water-quality measurements for all samples in all events (drawing by author).

The upper and lower points on the vertical lines indicate the maximum and minimum measured values. The upper and lower points of the blue rectangles indicate the first and third quartiles, while the horizontal line indicates the median value [10].

The charts in Fig. 2 allow several important conclusions to be drawn. For most parameters, including heavy metals such as copper and zinc and total suspended solids, the pervious concrete system achieves a clear reduction compared to untreated runoff, confirming its role as an effective geochemical and physical filter. However, certain parameters, notably turbidity and sulfate (SO_4), show elevated values in treated or snowmelt sample types compared to untreated stormwater. The higher turbidity observed in snowmelt samples can be attributed to the seasonal accumulation of fine particles on the pavement surface, which are mobilized during the first flush of snowmelt, as well as to the gradual release of fine cement-matrix particles from the PC surface itself. The elevated SO_4 concentrations in treated samples reflect leaching of sulfate-bearing hydration products from the cement paste, particularly calcium sulfate phases, which are moderately soluble in contact with percolating water. This leaching effect is typically most pronounced in newer installations and tends to diminish over time as the reactive phases are progressively depleted [10]. These observations underscore the importance of monitoring the full spectrum of water-quality parameters rather than limiting assessment to heavy metals or suspended solids alone.

Conventional PC shows notable potential for heavy-metal treatment. According to available results, high removal efficiencies can be achieved for zinc and copper in runoff, with the alkalinity of the cement paste playing an important role in metal immobilization [9], [10], [11].

The long-term sustainability of this mechanism depends on material composition, pollutant type, and exposure regime. Available findings indicate that systems incorporating recycled or geopolymer-based components may also retain good heavy-metal removal efficiency, which opens additional possibilities for coupling stormwater treatment with lower-carbon material design [20].

In addition to heavy metals, PC can contribute to lower concentrations of other pollutant groups such as suspended solids, organic loads, and selected organic compounds when compared with untreated runoff from impermeable surfaces [10]. At the same time, the same retention processes that support water-quality improvement may accelerate clogging, which means that environmental performance and hydraulic durability must be evaluated together rather than separately.

5. DURABILITY AND MAINTENANCE OF THE SYSTEM

Long-term hydraulic efficiency of pervious concrete is primarily threatened by clogging. Clogging occurs when sediments and fine particles carried by stormwater penetrate into the pore structure and progressively reduce the connected void network available for flow [16], [17], [21].

Studies show that particle size has a decisive effect on permeability degradation. Fine particles such as clay and silt are particularly unfavorable because they remain active within the pores for longer periods and can penetrate deeper into the structure than coarser particles [17], [21]. The influence of aggregate gradation on the spatial distribution of clogging under different hydraulic loading conditions is illustrated in Fig. 3.

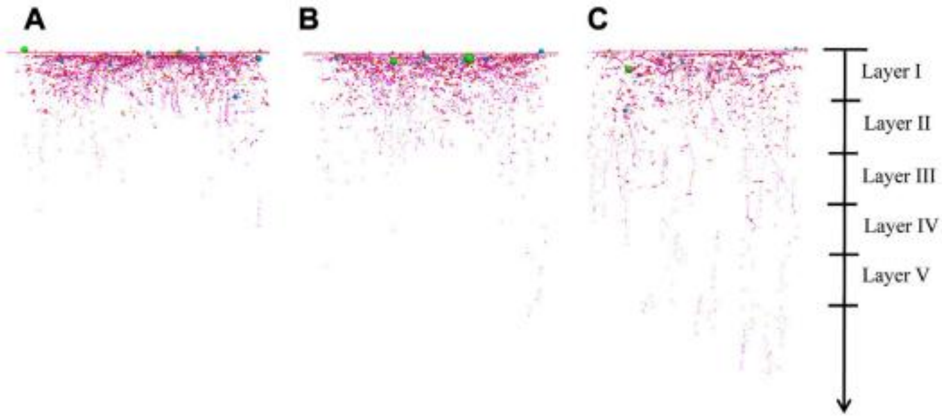

Figure 3. Clogging simulation test under gravity-driven and flowing-water conditions: (A) PA1; (B) PA2; (C) PA3 [17].

Figure 3 presents a numerical simulation of the clogging process under two hydraulic regimes: gravity-driven percolation (still-water conditions) and flowing-water conditions with lateral flow components. PA1, PA2, and PA3 represent three pervious concrete specimens with different aggregate gradations, ranging from coarser (PA1) to progressively finer (PA2 and PA3). The uniform grain colors used in the simulation indicate distinct particle size classes of the clogging material: red grains represent fine particles (silt and clay fraction), blue grains correspond to medium-sized particles, and green grains represent coarser sand-sized particles. The figure demonstrates that specimens with finer aggregate gradation (PA3) are more susceptible to deep clogging, because their narrower pore throats trap particles throughout the full depth of the pavement rather than concentrating deposition near the surface. In contrast, coarser gradations (PA1) tend to exhibit more surface-concentrated particle accumulation, which is generally easier to recover through vacuum sweeping or high-pressure washing [17].

Advanced characterization methods are essential for understanding this mechanism. Two-dimensional and three-dimensional CT imaging enables non-destructive visualization of pore morphology and of the spatial distribution of particles responsible for clogging, while numerical models help explain how pore geometry, inflow regime, and particle properties interact during progressive permeability loss [17], [18], [19], [20], [21].

To extend the service life of PC, effective permeability-recovery methods are required. Numerical simulations and laboratory studies indicate that combined cleaning approaches, especially vacuum sweeping followed by high-pressure washing, can be more effective than a single cleaning method, particularly when both fine and coarse deposits must be removed [16].

These findings support a transition from reactive to planned and technically informed maintenance. Integrating three-dimensional clogging characterization and numerical modeling into maintenance planning can help design targeted protocols that maximize permeability recovery and prolong service life instead of relying on universal but often ineffective maintenance routines.

In practical terms, the appropriate cleaning frequency depends strongly on the characteristics of the contributing catchment and the physicochemical quality of the stormwater runoff. As a general guideline, vacuum sweeping is commonly recommended at intervals of one to two times per year under average urban conditions, while sites with heavy sediment loads, dense tree canopy, or significant winter sand and grit application may require quarterly intervention. High-pressure washing, which is more effective for removing fine particles lodged deep within the pore structure, is typically applied every one to three years. The most reliable approach is to base maintenance scheduling on periodic in-situ infiltration measurements rather than fixed time intervals, since the rate of permeability decline varies considerably with site-specific conditions [16], [21].

Freeze–thaw durability is another critical issue in cold climates. The material is sensitive to freezing and thawing cycles, particularly in the presence of deicing salts [15]. Studies indicate that selected mix modifications, including supplementary cementitious materials and fibers, can improve resistance to freeze–thaw deterioration and surface distress [26]. It is important to note that PC does not fail immediately upon exposure to subzero temperatures. Damage accumulates progressively over repeated freeze–thaw cycles, particularly when the open pore network is water-saturated and simultaneously exposed to deicing salt solutions, which lower the freezing point and increase the hydraulic pressure of ice formation within the pores. PC is in fact used successfully in cold-climate regions of central Europe, including Germany, where freeze–thaw cycles occur regularly. In such contexts, mixture design is adapted to improve frost resistance: the water-to-cement ratio is reduced, supplementary cementitious materials such as silica fume or fly ash are incorporated to densify the cement paste around aggregate contacts, and air entrainment is introduced to provide expansion space for ice and thereby reduce internal pressure. These adaptations can substantially increase the number of cycles the material withstands before significant permeability loss or surface raveling occurs [15], [26].

Polypropylene fibers may also contribute to greater resistance to raveling and surface damage, which are common problems in highly porous materials [26]. According to available findings, fiber reinforcement can increase the energy required for full failure and improve abrasion resistance, thereby extending pavement service life under operational conditions [27].

6. MULTIFUNCTIONALITY AND INTEGRATED SUSTAINABILITY

The urban heat island (UHI) effect represents an important environmental and energy challenge in densely built areas. Pervious concrete can help mitigate this effect primarily through evaporative cooling [12]. After rainfall, water stored within the porous system evaporates and consumes latent heat from the pavement, reducing surface temperature.

Studies have shown that permeable concrete cools faster than conventional concrete after rainfall, which directly indicates more effective heat dissipation through evaporation [28]. Available studies report pavement surface temperature differences between PC and conventional concrete of up to several degrees Celsius under post-rainfall conditions, with the advantage of PC being most pronounced during the hours immediately following a rain event and persisting as long as stored water remains available for evaporation [28]. The porous structure of PC retains a substantially larger volume of water per unit surface area than an impermeable pavement, which means that evaporative cooling is not only more intense but also longer-lasting. This extended cooling effect can therefore lower near-surface air temperatures more effectively than conventional concrete, both immediately after rain and during subsequent dry periods as water gradually evaporates from within the pore system [12], [28]. In comparison with denser asphalt materials, PC and related permeable pavements can provide more favorable thermal behavior for UHI mitigation [29]. This dual function—stormwater control and surface cooling—strengthens the rationale for broader application.

The high porosity of PC may also provide acoustic benefits. The open pore structure can act as a sound-absorbing medium and thus contribute to lower traffic-noise levels in urban areas [13]. Acoustic performance is commonly described through indicators such as the sound absorption coefficient and the noise reduction coefficient, which are influenced by pore geometry, thickness, and surface conditions [22].

Life-cycle assessment (LCA) plays an important role in the environmental evaluation of PC systems, particularly when reduced carbon footprint is considered together with the use of recycled or composite mineral materials [18], [19], [20], [21], [22], [23]. When all co-benefits are considered together - runoff control, water-quality improvement, thermal effects, and potentially lower environmental burdens - the sustainability value of pervious pavements becomes more visible.

At the same time, broader acceptance of PC within regulatory and design frameworks for stormwater management remains a challenge. Therefore, long-term data on field performance, maintenance, and whole-life impacts are still needed for more confident integration of PC into urban sustainability strategies.

7. RESEARCH GAPS AND FUTURE RESEARCH

Although the knowledge base on pervious concrete has expanded significantly, a clear gap remains between laboratory investigations and field performance. Many studies report favorable results under controlled conditions, yet much less is known about the long-term interaction among traffic loading, site-specific sediment sources, climatic variability, and maintenance frequency under real service conditions.

A second important gap concerns the integration of mechanical, hydraulic, and environmental properties into unified design criteria. A considerable number of studies consider only one aspect - such as strength, permeability, or water quality - whereas actual engineering performance depends on the balance among these requirements. Future design methods should therefore address the permeability–strength trade-off more explicitly and incorporate durability and maintenance considerations at the design stage.

Further research should also be directed toward more reliable construction-control protocols, standardization of field monitoring procedures, and long-term evaluation of systems in different climatic settings. Particular attention should be paid to clogging diagnostics, predictive maintenance, and the development of low-carbon, recycled, and geopolymer-based pervious systems whose environmental benefits can be demonstrated under realistic operational conditions.

8. CONCLUSION

Pervious concrete is a promising solution for addressing the challenges of urban stormwater management and climate adaptation. Its primary value lies in reducing surface runoff and supporting infiltration, while additional benefits may include pollutant retention, mitigation of pavement-surface heating, and, in certain conditions, acoustic improvement.

The reviewed literature shows that the performance of PC is highly sensitive to construction quality. Excessive compaction can significantly reduce permeability and create non-uniform pore structure, while clogging by fine particles remains the principal mechanism of long-term degradation. Freeze–thaw exposure, especially in the presence of deicing salts, further complicates the durability of the system.

For broader and more sustainable application, it is necessary to improve construction control, develop more reliable maintenance protocols, and expand the evidence base on long-term field performance. In parallel, life-cycle studies and lower-carbon material modifications should be further developed so that environmental and functional benefits can be assessed together rather than separately.

On the basis of the reviewed literature, it can be concluded that pervious concrete has substantial potential as a component of green infrastructure, but its successful application is not automatic. Clearer design, construction, and maintenance guidance is required, together with better integration of hydraulic, durability, environmental, and sustainability criteria into practice.

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