Advances in Pervious Concrete: Hydraulic Performance, Durability, and Sustainable Material Applications

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ABSTRACT

Pervious concrete is an advanced, ecological-oriented material, the performance of which is defined by the interactions between porosity, permeability, density and compressive strength. Though higher hydraulic efficiency is achieved but this is counterbalanced by a progressive optimization mix of the matrix with reduction in compressive strength (3-25 MPa) in accordance with increase in porosity. This is a result of reduced interparticle contact and a proportional decrease in density of about 3.5-5% per 1% increase in the void content. A significant 55-65% strength loss (as porosity increases between 20-30%) has been reported, reflecting a less compact internal structure. To obtain a balanced performance it is necessary to optimize mix design, in particular by balancing the water-cement ratio between approximately 0.25-0.30, the appropriate gradation of aggregates, and the incorporating recycled and natural aggregates. Furthermore, the addition of cementitious material and fibers will enhance strong bonding in the microstructure and durability with minimal loss in permeability. Even though pervious concrete has massive potential as a sustainable pavement material, and the beneficial effect on stormwater managing, urban heat-reduction, further development of material engineering and environment friendly construction process is steadily increasing its functional reliability, thus strengthening its contribution to sustainable and climate-resilient urban infrastructure.

Keywords: stormwater; recycled aggregate; permeability; durability; porosity

INTRODUCTION

The increasing construction in urban areas combines with an expansion of concrete pavements in these built-up regions. Standard concrete pavements have poor water and air transmission properties which prevent rainwater from entering the soil. For normal plant growth people need ongoing water supply within the soil (J. Yang & Jiang, 2003). Transportation infrastructure high-impact development includes the construction of standard pavements which transforms naturally porous surfaces into impermeable land areas (Chandrappa & Biligiri, 2016; J. Li et al., 2017). Early rainwater purification occurs within the open structure of pervious pavement while it functions as a thermal and moisture passageway between atmosphere and pavement surface generating advantageous environmental effects (Xie et al., 2019). The fast expansion of impermeable surfaces combined with multiple issues such as heat island effects and tire-pavement noises and groundwater depletion and traffic safety conditions create rising demand for this material since PC can potentially solve these problems (Zhong et al., 2018). Pervious concrete pavement represents the most effective solution for groundwater protection and environmental preservation since it demonstrates better performance than alternative options in every structural and Hydraulic and economic aspect (Guntakal & Selvan, 2017). The basic and cost-effective method of waste tire disposal includes burning it. The pollution hazard from this method stems from big dust clouds and fume emissions into the environment. The current situation requires new recycling methods for used tires because of their standing. Concrete manufacturers utilize scrap tires as an option to use recycled waste tire products.

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Multiple studies have examined how recycled rubber affects typical concrete mixtures according to research investigation (Obla, 2010).

According to the granite-based pervious concrete mixtures displayed better performance than limestone-based mixtures although showing minor performance discrepancies. Scientific evidence found that polypropylene fibers either had no effect or caused no change to mechanical properties or abrasion resistance (Ozel et al., 2022). The structural designs of pavements built with PC depend heavily on measuring flexural and splitting tensile strength (J. Li et al., 2023). Additionally for environmental protection the implementation of recycled aggregates as partial replacements of natural coarse aggregate has started gradually (Wu et al., 2022). Permeable pavement functions as green infrastructure for close-source stormwater management (Eisenberg et al., 2015). For many years permeable pavement has existed though its storm water quality benefits across different types remain uncertain due to recent advancements in design, construction and maintenance methods (Kuruppu et al., 2019). The increasing global temperature from greenhouse gas emissions particularly carbon dioxide is producing extensive climate change issues. Extreme weather events have become more frequent alongside growing to persist longer durations thus leading to enhanced rainfall quantities and short-term intensity levels (Singer et al., 2022). Research on pervious concrete properties when using waste materials instead of cement has increased according to the elevated cement consumption. Researchers have established that the thickness level of cementitious material coatings serves as a vital factor to determine pervious concrete Hydraulic as well as structural performance (Khankhaje et al., 2024). Although the preexisting top concrete layer harbour numerous spaces which would function as temporary storage space for stormwater during rainfall it may delay the water runoff till complete saturation of the system occurs. The land surface's potential for water absorption determines the speed of rain runoff. The water flow rate within pervious concrete measures 0.2 cm/s through 1 cm/s while its porosity falls between 15% and 30% based on how it is positioned and what materials are employed (Haselbach et al., 2006).

This concrete type provides multiple benefits similar as sound damping, temperature reduction and ecological stability, groundwater recharge capabilities and stimulant for factory growth. The necessity for new seamster installations diminishes when porous pavement effectively infiltrates the soil. By minimizing the necessity for stormwater ponds and affiliated safety issues, PCP can drop the liability of legal problems for inventors or property possessors (Joshaghani et al., 2015). Lately, porous concrete has been honored for its environmental advantages and its implicitness to alleviate the heat islet effect, making it eligible for instrument in construction systems under the US Green Building Council's Leadership in Energy and Environmental Design (LEED) Green Building Rating System (Putman & Neptune, 2011). To address the issue of stormwater operation, which is a significant challenge in civic areas, the idea of Sustainable Civic Drainage Systems (SUDS) was developed (Elizondo-Martinez et al., 2020). In recent times, the miracle of "flash cataracts" has led to frequent circumstances of "extreme downfall events" storms and cataracts come after violent heat swells and extended famines. The drainage of total rainwater quantities to 40 evapotranspiration and 50 infiltration and 10 face runoffs in natural soil conditions (Moretti et al., 2019). Chinese authorities introduced the sponger megacity conception for the first time in 2012. The evaluation of sponger megacity construction as an airman program started in 30 Chinese metropolises beginning in 2015. Sponger megacity, which refers to a low impact development rainwater system. This innovative idea represents metropolises which acclimatize to water terrain variations like a sponge by letting water pass freely through their structure (Guan et al., 2021). Due to their multiple unique features polymers give numerous implicit operations and demonstrate both adaptability and continuity in addition to easy water saturation (Giustozzi, 2016).

REVIEW METHODOLOGY

This review adopts a systematic methodology to synthesize global research advancements in pervious concrete (PC) technology, specifically evaluating its hydraulic performance, structural durability, and sustainable material applications. The structured analytical process is executed through the following four distinct phases:

- Scope Definition and Theme Identification: The primary scope focuses on identifying the mechanical trade-offs inherent in PC design-specifically how the interconnected void ratio (typically 15% to 35%) fundamentally governs water transmission capability at the cost of reduction in compressive strength.

Core review domains include mix optimization parameters (water-cement ratios of 0.25-0.30, aggregate gradations, and fiber reinforcement) and environmental impacts.

- Literature Search and Material Classification: Secondary research data from prominent international studies (such as ACI, NRMCA, and various global engineering journals) are compiled. The selected literature is systematically grouped into two main analytical streams: baseline engineering performance metrics (porosity, density, permeability, and compressive strength) and operational durability challenges (clogging mechanisms and cold-climate freeze-thaw vulnerability).
- Comparative Cross-Study Analysis: Quantitative data are extracted and evaluated via cross-study matrix comparisons. This includes mapping structural performance deviations across different raw materials, specifically contrasting natural coarse aggregates against alternative sustainable elements like recycled coarse aggregates (RCA) and industrial waste by-products (fly ash and slag).
- Synthesis and Trend Forecasting: Findings are consolidated to establish the multi-functional viability of PC within Sustainable Urban Drainage Systems (SUDS). Finally, the methodology bridges current structural limitations with targeted future exploration areas, evaluating the integration of lifecycle carbon accounting, microbial self-healing agents, and artificial intelligence models for long-term clogging predictions.

BASIC DESIGN CONSIDERATION OF PERVIOUS CONCRETE

The sustainable material known as pervious concrete features connected pores that enable water movement through its structure (Chandrappa & Biligiri, 2016). Pervious concrete applications for pavement need engineering for sufficient strength against targeted traffic needs combined with beneficial stormwater handling at each site (Tennis et al., 2004). Pervious concrete pavements exist in two functional capacities including their use as infrastructure for pavement applications and stormwater management infrastructure. Technology represents a low impact development since implementation does not modify the natural water cycle in the same way as standard impervious paving systems (Henderson, 2012). Pervious concrete exhibits reliable long-term operation which results from well-designed and correctly placed structures and adequate maintenance work. Pervious concrete pavements can operate as main collector streets and residential thoroughfares for 20-30 years when constructed properly to yield results similar to standard concrete pavements (Xie et al., 2019). The designer evaluates multiple criteria including material selection and pavement height and other key characteristics for achieving Hydraulic requirements and handling expected traffic loads together. Pervious concrete finds application across multiple sectors because of its ability to permit high-level waterflow. Pervious concrete requires strength and permeability to be suitable design factors according to Cui et al., 2017. The hydraulic along with structural design aspects of designing pervious concrete pavements are outlined in this section according to reference (Tennis et al., 2004). Pervious concrete serves as one of the permeable pavement materials to deliver traffic safety and better road environments. A central drawback in pervious concrete operation that diminishes its environmental capabilities is known as clogging because it affects its permeable characteristics (Zhou et al., 2019). Complete procedures must be followed starting from appropriate composition design through the execution steps to end with final quality control measures described by the ACI (American Concrete Institute) (Sicakova, A., & Kovac, M. , 2020; Tennis et al., 2004).

Structural Design Considerations

A comprehensive guide exists in this section for building structural designs in pervious concrete pavements. The procedures described offer both methodologies for analyzing existing data and methods to determine structural thicknesses of pervious concrete pavement designs. The design of pervious concrete pavements can proceed through standard pavement procedures like AASHTO, WinPAS, PCAPAV or ACI 325.9R or ACI 330R but also permits the use of structural numbers derived from flexible pavement design methods (Chandrappa & Biligiri, 2016). Various research shows parking lot pervious concrete pavements typically have 150 mm thickness although low-volume street pervious concrete installations range between 150 and 300 mm thick (Hamdy, 2016).

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Low ADTT truck-exposed parking lots should contain 6 in. (150 mm) of pervious concrete pavement according to NRMCA (2007) recommendations (J. Kevern, 2010).

Hydraulic Design Considerations

Developing a pervious concrete pavement design requires multiple aspects for evaluation. Three main factors include forecasted rain precipitation together with pavement conditions and underground soil composition (Tennis et al., 2004). The unrestricted flow of rainfall storms threatens both water quality and environmental systems while causing drainage problems and flash floods (Imran et al., 2013). Under traditional pavement design approaches operators try to maintain water from penetrating into the subgrade soil below the pavement. The main function of porous paving creates water saturation of subgrade materials which are located beneath the pavement surface. The subgrade properties should be evaluated while considering this condition. The density of a soil increases when the soil receives compaction so its pores become smaller. The lower compaction density of pervious paving subgrades serves as standard practice because it suits their different function than traditional concrete paving subgrades. The necessary punch density reaches 90% Standard Proctor Maximum Dry Density (Obla, 2010). The system design through the reservoir system depends heavily on hydrologic considerations which have received full development. The reservoir section has its base in the subgrade which could be separated from it by geofabric layers. All layers/components described here may exist in specific section designs but not every application includes full implementation of all elements (J. Kevern, 2010; Schaefer et al., 2006). Engineers need to ensure pervious concrete pavement systems bear rainfall amounts which exceed what would fall naturally on the pavement. An active system should be implemented for site runoff management to reach specified control levels (Tennis et al., 2004).

Other Design Factors

The production method for pervious concrete uses combinations of water cement and uniformly sized coarse aggregate with moderate content of fine aggregate (Berry et al., 2012). The strength and permeability values obtained from pervious pavement mix designs depend on the amount of compaction specified in the design phase (Tennis et al., 2004). The permeability coefficient shows optimal results at a water-cement ratio of 0.30 and fiber addition results in better flexural strength performance of pervious concrete (L. Guo et al., 2020). The combination of water reducing and air entraining admixtures received recommendation in research (J. T. Kevern, 2008). Weight-based principles maintain the consistency of aggregate-cement ratio according to (Zhang & Gao, 2019). The final cementitious content in pervious concrete mixtures determines compressive strength development along with void structure formation because inadequate cement materials cause reduced aggregate paste coating and diminished strength outcomes. Aggregates' dimensions and their distribution directly dictate the best amounts of cementitious products needed (Bakshi et al., 2016). The material composition of pervious concrete mix includes cement ranging from 270 to 415 kg/m^3 together with 1190 to 1480 kg/m^3 aggregate content (de Moura et al., 2021). Studies regarding pervious concrete use of super plasticizer have been extensively researched internationally but such studies incorporated air entraining agents as additional admixtures since they needed to adapt to their specific local conditions (Muthaiyan & Thirumalai, 2017). The selection of concrete mixture proportions together with purchase agreement conversion needs bulk density values as part of essential information (Tamimi et al., 2023). Very few publications exist regarding the method for designing pervious concrete mix. The American concrete institute method together with Zouaghi's method and Zheng's method form a list of approaches (de Moura et al., 2021). Figure 1 represents typical percentage of different ingredients in pervious concrete as presented by Binitha et al. (2017).

CHARACTERISTICS OF PERVIOUS CONCRETE

Previous research shows that the size and gradation of aggregates, porosity and the water-cement ratio affect the permeability properties of pervious concrete to a different degree (Shan et al., 2022).

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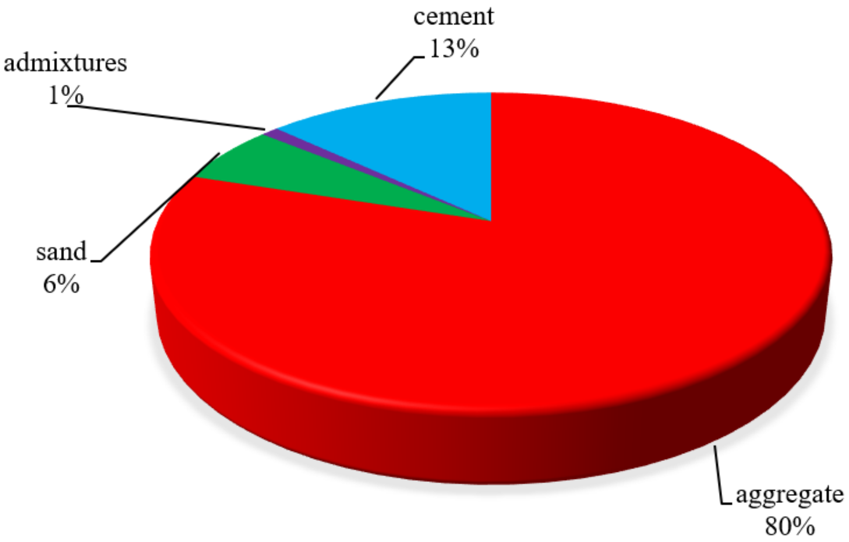

Figure-1: pervious concrete ingredients (Binitha et al., 2017).

Porosity

The permeability features of pervious concrete depend mainly on pore characteristics (Shan et al., 2022). Pervious concrete achieves weight reduction due to absence of fine aggregates, yet its insulation strength rises because air exists within the voids that the aggregates left behind. The interconnecting void channels in pervious concrete serve as passageways that let water penetrate the soil strata beneath to lower surface runoff water discharge (Shrestha et al., 2022). Effective water penetration occurs through porous concrete materials which contain connected void spaces between 0.08 to 0.32 in. (2-8 mm). The range of void content extends from 15-35 percent according to (Elango et al., 2021). Mixtures consisting of blended aggregates acquired the lowest void content through the process of higher size aggregates filling void spaces with lower size aggregates (Leon Raj & Chockalingam, 2020). The strength characteristics of conventional concrete are usually much greater than pervious concrete because of its high porosity coupled with low cement/mortar content (Sicakova, A., & Kovac, M., 2020). The presence of small and numerous fine aggregate particles works together with reducing aggregate grain size to decrease void content (Huang et al., 2010; Kishore & Guntakal, 2017; Sicakova, A., & Kovac, M., 2020) Studies demonstrated that decreasing the void ratio of pervious concrete mixtures increased their compressive strength values (Chen & Zhang, 2009; Deo & Neithalath, 2011; Sicakova, A., & Kovac, M., 2020). All voids present in Pervious Concrete do not allow liquids to move freely. The separation of pores from each other makes those pores unusable for water penetration. The processing power from surface tension and capillary effect allows small-sized pores such as capillary pores and dead-ended pores to hold fluids (Zhong et al., 2018).

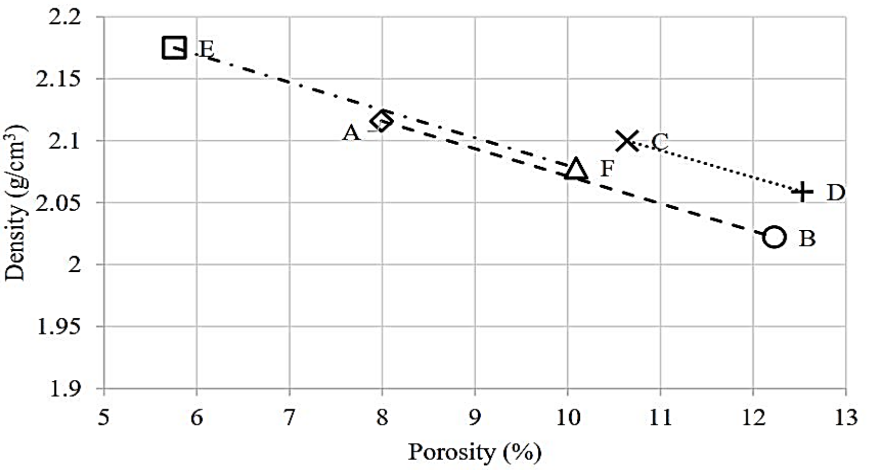

Figure -2: Relationship between porosity-density (Shrestha et al., 2022)

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Table-1: Summary of the previous porosity on pervious concrete

Observation	Description
Effect of w/c Ratio and RCA replacement on effective void content	Concrete with a higher w/c ratio 0.3 consistently exhibits greater effective void content than that with a lower ratio 0.25. For both mixes, void content increases slightly as the recycled coarse aggregate (RCA) replacement rises from 0% to 40%. At w/c = 0.3, voids increase from 15.4% -16.0%, while at w/c = 0.25, they rise from 14.8% -15.3%. The trend shows an initial increase up to 10% RCA, followed by a gradual rise thereafter (Haselbach et al., 2006).
Relationship between density and porosity	Density decreases with increasing porosity, following a strong negative linear trend. For porosity levels of 25-28%, density ranges from 1920 to 1990 kg/m³, while at higher porosity levels of 28-31%, density decreases to 1830-1920 kg/m³, reflecting the inverse relationship between void content and material compactness (Costa et al., 2018). Similar pattern of decrease in density with increase in porosity was observed by Shrestha et al. (2022), as shown in Figure 2 and Tang et al. (2022), as shown in Figure 4.
Effect of porosity on compressive strength and permeability	Compressive strength decreases non-linearly with increasing porosity for both aggregates, with natural aggregate reaching 19 MPa and recycled aggregate 8 MPa at 20% porosity. In contrast, permeability increases sharply with porosity, reaching 8.5 mm/s at the same point. These trends highlight that higher porosity reduces strength while enhancing water flow, with recycled aggregate concretes showing lower strength than natural aggregate concretes at equivalent porosity levels (Sriravindrarajah et al., 2012).

Permeability

The permeability of pervious concrete depends primarily on the connected pores inside the material (Shan et al., 2022). The permeability of concrete mixtures containing small-sized aggregates remains lower than the mixtures containing bigger aggregate shapes. The permeability of pervious concrete depends on pore scale because it contains connected pores (Maguesvari & Narasimha, 2013). The selection of fiber dosage depends on exposure conditions together with specific concerns according to literature findings. The selected dosage of 1.5 kg/m^3 was proposed specifically for improving high permeability levels (Chandrappa & Biligiri, 2016). The reduction of aggregate grain size and increased amounts of fine material results in decreased permeability (Huang et al., 2010; Kishore & Guntakal, 2017; Sicakova, A., & Kovac, M. , 2020). Water permeability of about 2-20 mm/s was reported by Zhong et al. (2018), Tripathi et al. (2017) and Tang et al. (2022) (Figure 3 and Figure 4).

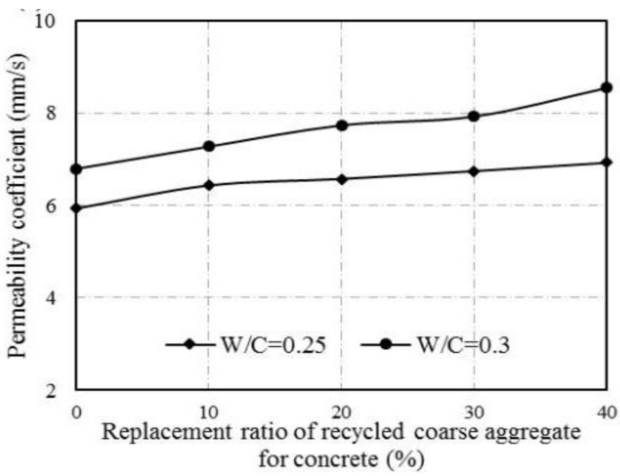

Figure-3: Replacement ratio of RCA VS permeability coefficient of pervious concrete (Dev Pratap Mani Tripathi et al., 2017).

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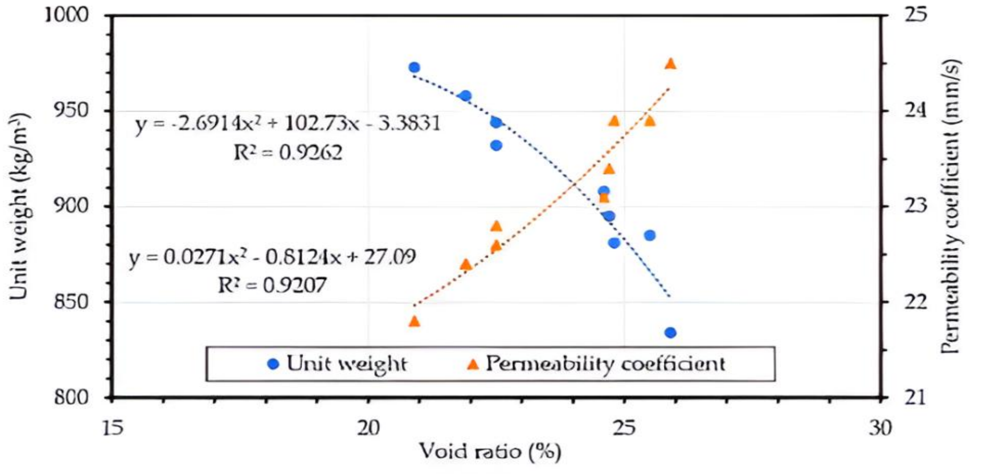

Figure-4: Unit weight and permeability coefficient versus void ratio (Tang et al., 2022).

Table-2: Summary of the previous permeability on pervious concrete

Observation	Description
Effect of cement content, fines, and fly ash on permeability	Permeability decreases with increasing cement content, fines, and fly ash, as higher cement and added materials fill void spaces. The highest permeability 1.6 cm/sec occurs at 0% fines and fly ash with 200 kg/m³ cement, while the lowest 0.4 cm/sec is observed at 15% fines with 20% fly ash at 250-300 kg/m³ cement (Putman & Neptune, 2011).
Relationship between density & permeability	Density inversely related to porosity. Higher porosity corresponds to lower density, while lower porosity indicates higher density. As porosity and permeability decrease, it can be inferred that permeability decreases with increasing density. This aligns with typical behavior in pervious materials, where denser mixes reduce flow channels, resulting in lower water permeability (Moretti et al., 2019).
Effect of w/c ratio and recycled aggregate on permeability	Concrete with a higher w/c ratio 0.3 consistently exhibits higher permeability than that with a lower ratio 0.25 across all replacement levels. For both w/c ratios, permeability increases with the replacement of recycled coarse aggregate 0-40%. Specifically, for w/c = 0.3, permeability rises from 6.8 mm/s at 0% replacement to 8.5 mm/s at 40%, while for w/c = 0.25, it increases from 6.0 mm/s to 7.0 mm/s over the same range. The increase appears linear or slightly upward-curved, indicating that higher recycled aggregate content consistently reduces water flow resistance (Haselbach et al., 2006).
Effect of void content on water permeability	Water permeability increases exponentially with void content. At low void content 15%, permeability is minimal 50 in./hr, whereas at high void content 34%, it exceeds 2000 in./hr, with the fitted curve reaching 2700 in./hr. Despite some scatter between 20-25% void content, the overall trend clearly shows that higher porosity dramatically enhances water flow (K.Wang et al., 2006).

Compressive Strength

A material designer focuses on compressive strength as the key property for concrete development yet pervious concrete shows strength measurements between 3-25 MPa (Chandrappa & Biligiri, 2017; Dash & Kar, 2018: Nguyen et al., 2014). Research demonstrates that fine aggregate enhances pervious concrete compressive strength but fiber addition does not produce significant strength improvement. The pore structure characteristics should be considered essential factors in pervious concrete compressive responses (Liu et al., 2020). Silica fume provides concrete with considerable strength enhancement. Glass powder addition improves porous concrete durability with strength characteristics enhancement and better workability potential according to research (L. Guo et al., 2020).

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Table-3: Summary of the previous compressive strength on pervious concrete

Observation	Description
Variation of compressive strength based on %RCA and density.	Compressive strength increases with density, confirming a positive correlation. Concretes with 0-20% RCA show the highest strength and density, while 100% RCA mixes exhibit the lowest values, reflecting the negative impact of full replacement. Intermediate levels 10-50% RCA fall between these extremes, indicating that partial RCA use ≤20% is feasible with minimal strength loss, whereas higher contents significantly reduce performance (Elizondo-Martinez et al., 2020).
Compressive strength of pervious concrete for various cement contents, percentage of fines and fly ash replacements.	Compressive strength increased with cement content, with 300 kg/m³ mixes showing the highest values and 200 kg/m³ the lowest. The maximum strength 14 MPa occurred at 15% fines and 0% fly ash, while the minimum 7 MPa was observed at 0% fines and 0% fly ash. Increasing fly ash replacement 0-20% generally reduced strength, especially in high-cement mixes. Overall, higher fines and cement contents enhanced strength, whereas excessive fly ash reduced performance (Putman & Neptune, 2011).
Effect of recycled aggregate/cement ratio on compressive strength.	Compressive strength decreases linearly with increasing Recycled Aggregate/Cement (RA/C) ratio, highlighting a clear negative correlation. Data points, ranging from RA/C = 3.8-7.2, show the highest strength 12.5 MPa at the lowest ratio and the lowest strength 5.2 MPa at the highest ratio. This trend underscores the adverse impact of higher recycled aggregate content on concrete strength (Cheng et al., 2011).
Effect of fine-to-coarse aggregate ratio on compressive strength.	Compressive strength generally increases with the percentage of fine-to-coarse aggregate in the mix. The lowest strength 4.5 MPa occurs at 0% fine-to-coarse aggregate, while the highest strength 7.3 MPa is observed at 11.7%. Strength values appear to plateau beyond 4.7%, with mixes containing 4.7%, 8.1%, and 11.7% all achieving similar strengths around or above 7 MPa, suggesting that a moderate increase in fines is sufficient to optimize compressive performance. (Moretti et al., 2019).
Effect of effective void content on compressive strength.	Cubic compressive strength decreases sharply with increasing effective void content, following a strong negative power relationship. The highest strength 23.5 MPa occurs at the lowest void content 14.8%, while the lowest strength 19.7 MPa corresponds to the highest void content 16.05% (Haselbach et al., 2006).
Compressive strength of five different concrete Mixes (cement to coarse aggregate ratio, A1 to A5) based on their w/c ratio.	The mix with a cement to coarse aggregate ratio, A1 1:4 and w/c = 0.3 achieved the highest 28 days strength 34.3 N/mm², whereas the, A2 1:7 ratio with w/c = 0.4 produced the lowest strength 14.44 N/mm². Lower w/c ratios clearly enhance compressive strength, with mixes A1 and A2 outperforming the higher ratio mixes (A3-A5). Additionally, curing time significantly improves strength, as all mixes exhibit substantial gains from 1 to 28 days (Tripathi et al., 2017).
Splitting tensile strength based on replacement rate of coarse aggregate with RCA (%)	Splitting tensile strength is significantly lower than compressive strength and exhibits smaller variation. It starts at 1.6 MPa for 0% replacement, peaks at 1.9 MPa at 25%, and then decreases to 1.5 MPa at 50%, remaining constant at 75% replacement (Singer et al., 2022).
Effect of aggregate size on cylindrical compressive strength	Cylinder strength decreases with increasing porosity, showing a clear negative correlation. Concrete with 13 mm aggregates achieves higher strengths 11-16 MPa at lower porosity 25-30%, while 20 mm aggregates result in lower strengths 6-8 MPa at higher porosity 30-

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	37%. The two data sets are largely distinct, emphasizing that smaller aggregate sizes enhance strength by reducing porosity (Sriravindrarajah et al., 2012) (Figure 5 and 6).
Effect of fine aggregate content and coarse aggregate size on compressive strength.	Compressive strength increases with fine aggregate content, especially between 20-30%, and is consistently higher for smaller coarse aggregates. Maximum strengths at 50% fine aggregate range from 26.2 N/mm² (4.75-9 mm) to 23.6 N/mm² (16.5-19 mm), while initial strengths at 0% fine aggregate are lower 9.8-10.8 N/mm². Strength gains slow beyond 40% fine aggregate, indicating diminishing returns at higher contents (Khankhaje et al., 2024).

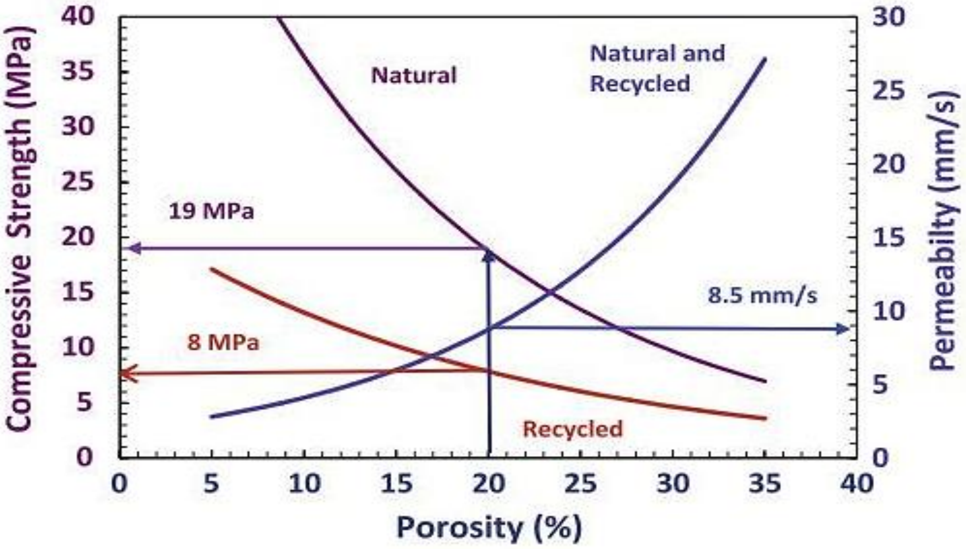

Figure-5: Relationships between porosity, strength and permeability for pervious concrete (Sriravindrarajah et al., 2012).

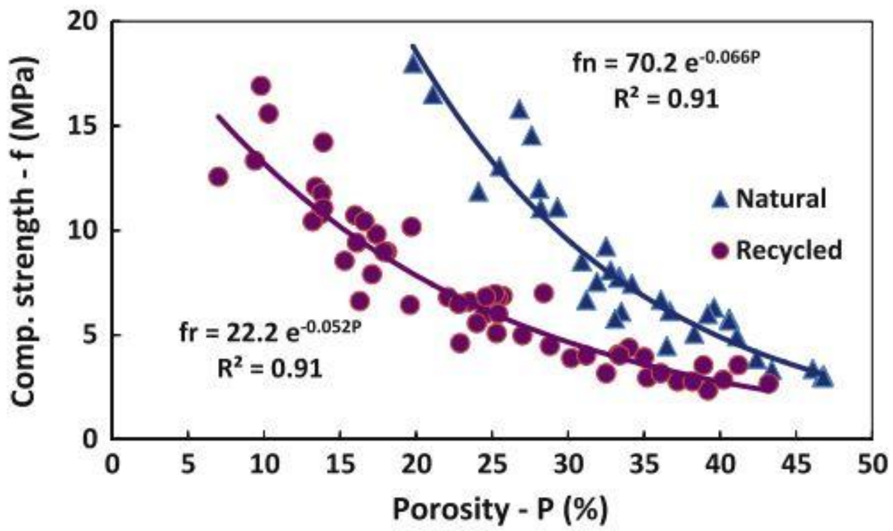

Figure-6: The type of aggregate on the porosity and strength relationship on pervious concrete (Sriravindrarajah et al., 2012).

Sustainability

Pervious Concrete demonstrates suitable uses in ground water recharge alongside storm water management as well as noise reduction for controlling surface run-off and temperature behaviors with pollution retention sinks (Chu & Faw, 2019; Wang et al., 2006). When installed on permeable pavements as a coating pervious concrete

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enhances water infiltration thus helping to lower surface runoff and boost natural aquifer recharge (de Moura et al., 2021; Selbig et al., 2019). Due to its high porosity pervious concrete promotes water evaporation while also playing a role in urban heat island reduction. Scientific studies demonstrate that this material possesses effective noise reduction capabilities and strong water retention properties because of this pervious concrete acts as a sustainable drainage system solution (El-Hassan & Kianmehr, 2018; Selbig et al., 2019; Sotor-Peerez & Hwang, 2016).

Benefits And Application of Pervious Concrete

Rather of soaking in the soil, a significant volume of rainwater is wasted on parking lots, driveways, and rambler roads, which further causes natural imbalances that affect flooding, soil erosion, and water reduction. Managing impermeable shells and switching to porous concrete, which has several advantages, is a well-known result to the issue (Chu & Faw, 2019). In Stormwater operation technologies pervious concrete lowers, the threat of civic flooding by lowering the drain pressure through peak inflow and overall runoff volume (J.Wang et al., 2022). Pervious concrete is generally only used in low business areas like sidewalks and parking lots (Bhattarai & Bhattari, 2023; X.Chen et al., 2019; Delatte & Schwartz, 2010). Three main processes were used by porous pavement to purify stormwater chemical sanctification to convert acidic stormwater into alkaline. Natural sanctification took place in the pores of porous pavement, which serve as a home for microbiological exertion, and physical sanctification to exclude solid suspended patches from stormwater. Civic stormwater runoff has been shown to effectively remove colorful heavy essence rudiments, total phosphorus, total nitrogen, and total suspended patches when porous concrete pavement is used (Y.Chen & Zhang, 2009). One green structure that might lessen the adverse environmental goods of stormwater runoff in metropolises is the porous pavement system, which is generally conceded to be effective (X.Chen et al., 2019).

It can lessen the civic heat islet effect and noise pollution, which is essential for the growth of sponger metropolises (Chen et al., 2020; T. Li et al., 2024). The underpinning strata of the pavement lost the capability to change energy with the advanced layers when the face was covered with undrainable pavement. This is one of the primary causes contributing to the civic heat islet effect (UHI). By allowing brume and thermal energy to escape from the face, porous concrete pavements can help balance the thermal heat outside (Adresi et al., 2023). Among the numerous environmental advantages of porous concrete are its capability to snappily and fluently absorb downfall and recharge groundwater (Tran et al., 2024). Because porous concrete acts as an urbanized drainage system, downfall can transude through its structure and gather in the base and subbase of the soil (Bhattarai & Bhattarai, 2023). Trees may thrive indeed in densely populated places because to porous concrete pavement, which permits air and water to reach root systems (Delatte & Schwartz, 2010). Because of dropped retention and evapotranspiration in urbanized regions, stormwater adulterants were stressed by the NRC (2008) as a primary source of water quality damage. Stormwater operation styles are essential for limiting the volume of runoff and adulterants since highways and parking lots were shown to be significant sources (Obla, 2010).

According to porous concrete, wells in one position may drain water from under other parcels, causing controversies between neighbors as groundwater shifts in response to pumping. Groundwater is a common-pool resource and raises the possibility of a traditional tragedy of the commons due to its propensity to breach property borders on a larger scale (Owen, 2021). Pervious concrete costs 15-25 further than other concrete, according to the Federal Highway Administration. In substance, it relies on many variables, including the operation fashion and the substance used. Full, partial, andnon-filtration pavement cost analyses are examined. Many studies have been conducted on the cost analysis of porous concrete (PC), according to the literature. As substantiated by the available data, PC construction is more expensive than other concrete (Khinvasara & Sonawane, 2020). By absorbing the first flush of face runoff, lowering incoming water temperatures, adding base inflow, and lowering the threat of cataracts, porous concrete can enhance water quality. The pavement causes downfall to be temporarily stored. For stray animals and pedestrians, it helps cool the temperature in the summer. Because rainfall percolates straight into the earth, there is no need for a wet pond or stormwater management pond. Reduces expenses for gutters, curbs, wet ponds, etc. Wintertime circumstances eliminate the need for deicing since water cools pavements. It reduced expenses for installation. This kind of pavement has a longer lifespan and costs less than ordinary pavement (Samadhana, 2023). According to a small number of studies, pervious concrete is more expensive initially and has a lower mechanical strength than standard CIC. However, just the

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original building cost is used to make these findings. Pervious concrete can lower life cycle costs by 30%, according to life cycle cost study (Zhong et al., 2018).

Pervious concrete applications include as concrete that has been previously pavement on roads, driveways, barriers to noise, stabilization of slopes, hydraulic constructions, decks for swimming pools, courts for tennis (Field et al., 1982). High situations of development with natural drainage and many porous shells are known as ultra-urban areas. Because porous concrete pavements exclude the need for stormwater retention systems, they're a good option in these types of settings because they help maximize land use (Elango et al., 2021). In discrepancy to country roads, porous concrete is used to pave metropolitan roadways, which infrequently allow rainwater to percolate. Also, these roadways have concrete crossbeams covering their platforms. The most recent trend involves covering the maturity of the spaces girding homes with concrete interlocking blocks, which can ameliorate a structure's aesthetic appeal. Consequently, runoff happens briskly in metropolises with advanced peak overflows. As cataracts and water adulterants downstream grow, so do flood tide volumes (Ong et al., 2016). As the insinuating water passes through the severance spaces, dissolved rudiments can be excluded by adsorbing onto the passable pavement itself or onto solid patches and the solids trapped inside the pavement. The suspended patches can be adsorbed with phosphorus, essence, organic acids, calcium, and PAHs. Heavy essence may be paralyzed by sorption, chemical objectification or macro-encapsulation (Zhong & Wille, 2018). Figures 7 and 8 represent permeable concrete layer arrangement and probable drainage system design suggestions that can be implemented for water collection, groundwater recharge and other purposes.

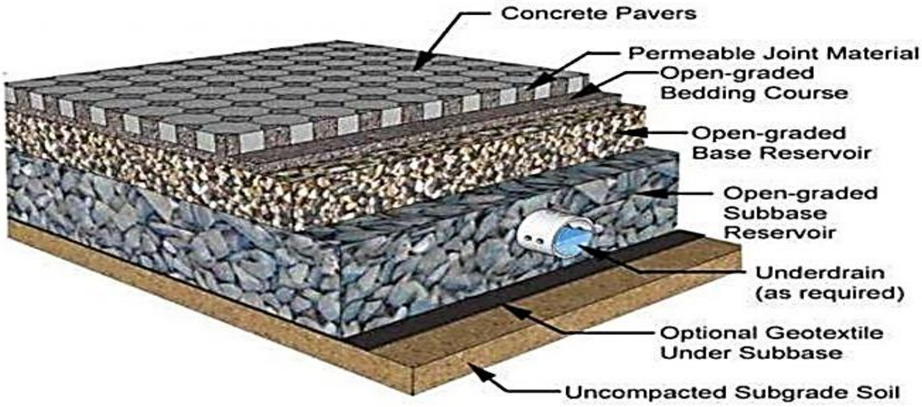
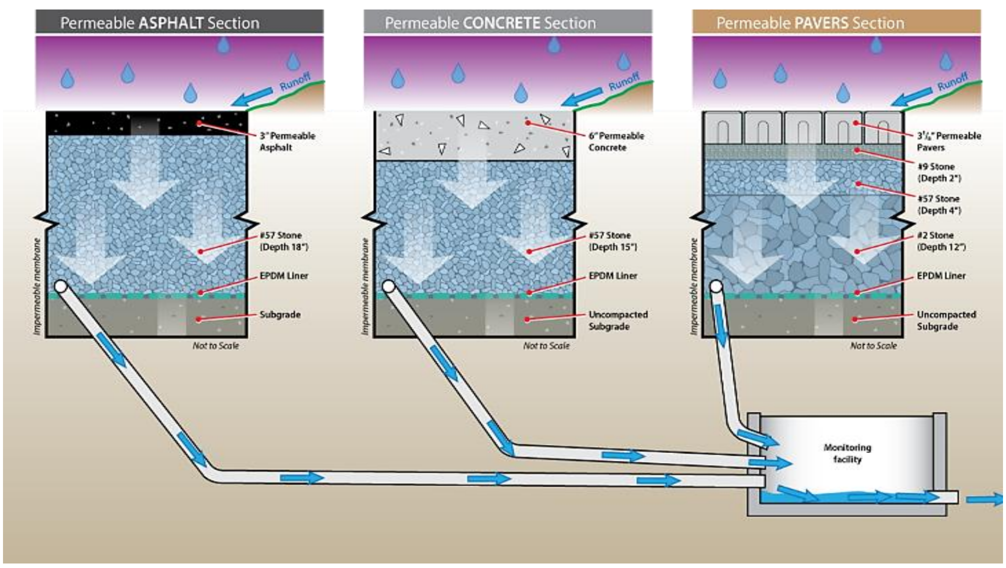


Figure-7: Layers in permeable pavement (Samadhana, 2023).



a)

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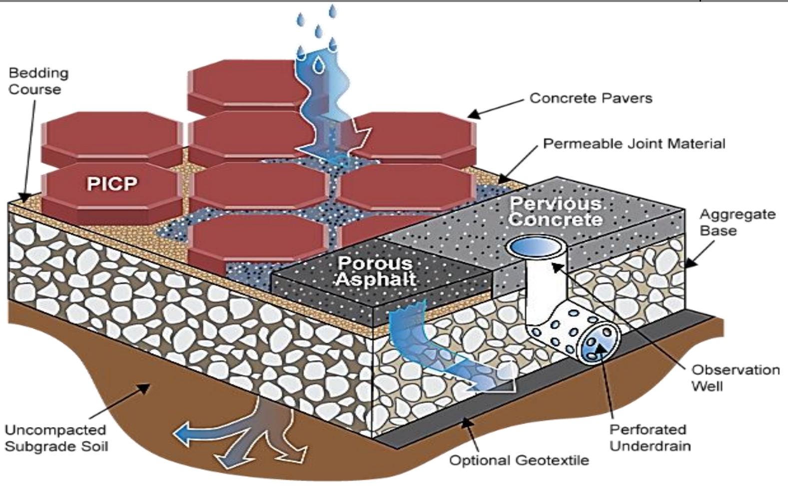

b)

Figure-8: a) and b) Drainage system provided by permeable section (Subramanian, 2008).

Challenges of Pervious Concrete

The main challenges PC technology encounters include weak resistance as well as filter clogging and material durability risks due to its porous design. At present the usage of PC exists mainly in parking lots and sidewalks since strength represents no crucial criterion (Sandoval et al., 2022).

Clogging

Clogging represents the main mechanism that causes hydraulic serviceability loss in this material (Lin et al., 2025). Figure 9 describes schematically the clogging mechanism in permeable pavement as described by Rahman et. al. (2025). The vibrations produced by passing vehicles present substantial obstacles to the effective operation of pervious concrete material by threatening its pore structure stability while decreasing clogging resistance and reducing durability levels. The material performance of previous concrete relies primarily on pore structure because it determines how well the material permeates while resisting clogging of its pores (Kia et al., 2018). The material easily becomes blocked by particulate matter and there are no proven methods to predict long-term performance of permeable concrete. How clogging affects the long-term performance of pervious concrete remains difficult to determine while no reliable approach exists to assess clogging potential for performance evaluation of different pavement systems (Yong et al., 2013). The operational performance of these systems heavily depends on clogging but scientists neither comprehend nor convincingly explain these processes. Evaluation studies indicate clogging occurs frequently across sites but comprehensive research into the underlying mechanisms that explain and measure this phenomenon practically does not exist (Adresi et al., 2024). The PC system addresses decreased clogging risk as its main operational goal (Z.Yang, 2011).

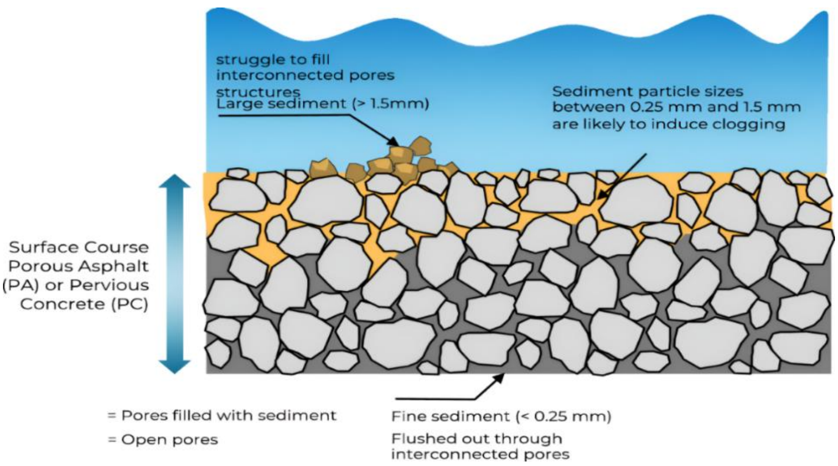

Figure-9: Clogging in permeable concrete (Rahman et al., 2025).

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Durability

The durability of pervious concrete mostly depends on its capabilities to endure freeze-thaw conditions. Its extensive porosity structure enables pervious concrete to accept water infiltration until freezing takes place during cold weather. Freeze-thaw sequences produce major structural damage to materials by making water expand upon freezing which creates weakening of the surface structure (Taheri et al., 2021). The durability challenges include difficulties in quantitative measurement of pervious concrete materials together with the development of quantitative links between physical and chemical traits and performance results of pervious concrete (Xie et al., 2019). Evaluating freeze-thaw durability of pervious concrete faces a main challenge based on the measurement procedures used to assess this parameter (Schaefer & Wang, 2006).

Initial Cost

The development of correct permeability strength with specified strength levels in pervious concrete depends on precise mix design and special materials selection. As a result of using high-quality materials the overall expenses surpass those of conventional concrete applications (Tennis et al., 2004). Proficient contractors along with specialized equipment are necessary to handle the installation of pervious concrete since it differs from traditional concrete methods. Installation costs rise because of its labor-intensive work procedures. The lifetime durability alongside permeability of pervious concrete depends on correct curing procedures and proper installation methods. Quality control measures such as in-situ permeability testing and maintenance planning require supplementary costs as part of the entire process (Joshaghani et al., 2014). Toward creating the required interconnected void network in pervious concrete, the specific aggregate gradation must consist of uniform-sized coarse aggregates only. The required aggregates for pervious concrete demand larger sums of money than the combination of aggregate sizes utilized in standard concrete (J.Guo et al., 2022). Structural design of pavements made from pervious concrete demands extra attention because its reduced compressive strength requires waste management. Additional materials might be necessary when implementing such structures because of the lower strength characteristics (Elango et al., 2021).

Limited Application in Cold Climates

Prior to concrete, water penetrates easily through its open structure. The ice that forms from this penetrating water in frigid conditions applies substantial force which damages the concrete boundaries. The concrete structure faces deterioration from repeated freeze-thaw action which leads to cracking and spalling (Shi et al., 2010). Deicing salts along with chemicals introduced in cold areas lead to more severe freeze-thaw damage. Failure of concrete occurs due to permeation of chemical substances through pores which results in crystallization problems leading to internal stresses and subsequent cracking (Chindraprasirt et al., 2008; J.T. Kevern et al., 2010)

Future Research Directions

Pervious concrete continues to rise in pavement applications because of its multiple advantages but additional research about the material will lead to its potential status as a sustainable road structure (Chandrappa & Biligiri, 2016). Additional cementitious materials such as fly ash, silica fume and slag enhance concrete strength together with durability measures (Jonkers & Schlangen, 2009; L. Wang et al., 2024). Polypropylene besides basalt steel and other fibers establish a vital role in making materials more resilient to cracking and tough (Jonkers & Schlangen, 2009). Microorganisms that form calcium carbonate serve as a method to seal micro-cracks (A. Wang et al., 2020). Assessing the energy usage together with greenhouse gas emissions that result from materials manufacturing and construction phase and site upkeep (Chiriac & Kiss, 2024). The application of AI models to analyze clogging trends and optimize maintenance strategies. The focus lies on improving filtration systems to improve the quality of stormwater (Zhong et al., 2018). Scientists investigate lignin and cellulose together with alternative natural additives to make cement stronger while decreasing amounts of cement usage. The effects of fiber reinforcement including steel and synthetic fibers and natural fibers on tensile strength and ductility should be investigated (Chiriac & Kiss, 2024).

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CONCLUSION

A sustainable substitute for traditional pavements, pervious concrete is cutting-edge building material. It is very useful for stormwater management and groundwater recharge because, unlike conventional concrete, it has interconnecting pores that let air and water pass through. These characteristic filters contaminants, heavy metals, and suspended particle when water seeps in, reducing urban floods, reducing soil erosion, and improving water quality.

Pervious concrete improves ecological balance, reduces noise, and facilitates evaporation and thermal exchange, all of which help to lessen the urban heat island effect. Its void content usually varies from 15% to 35%, resulting in seepage speeds of 2-6 mm/s. Although these attributes make it well-suited for light-traffic projects such as walkways, access roads, and vehicle storage areas, its structural durability is commonly less than standard cement, displaying compression resistances of 3-25 MPa. Enhancements are possible through the utilization of additional cementing substances such as pulverized fuel ash, silica fume and slag, alongside fibers like polypropene or steel. Even though permeable pavement has lots of environmental and community benefits, it faces problems such as pores getting clogged, damage from cold and warm weather in colder areas, high initial costs, and the need for special installation and care. In city areas, it is being used more and more in sustainable urban drainage systems (SUDS) and sponge city projects to handle sudden flooding and heavy rain. Future studies want to improve strength, durability, and clog resistance by using better mix designs, recycled and eco-friendly materials, fibers, and microbial crack repair. Also, artificial intelligence is being looked at to predict clogging and improve maintenance. With these improvements, pervious concrete pavement has a great chance to become a key material for sustainable and climate-resilient infrastructure.

Conflict Of Interest

The authors declare that there are no conflict of interests or personal relationships that could have appeared to influence the work reported in this paper.

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