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Advances in Pervious and Sustainable Concrete: A Review of Material Innovations, Mechanical Performance and Environmental Benefits

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Abstract

The concrete is the most common building material in the world but its production has been linked with tremendous environmental effects such as high CO_2 emission and natural resources depletion. Over the last few decades, permeable and sustainable concrete solutions have cropped up as possible ways of managing issues to do with urban flooding, heat island effects, and ecological degradation. This paper is a review of the current developments in the pervious concrete and sustainable concrete, based on a group of experimental and review research papers. Some of the material innovations that are analyzed include the use of palm oil fuel ash, recycled aggregates, addictive cementitious materials, and other industrial by-products. The results indicate that pervious concrete may have compressive strengths of 2-28Mpa, permeability coefficients of 0.25-47.7 mm/s, and high storm water management advantages. There are also innovative additives that enhance the skid resistance, abrasion resistance and durability. According to environmental tests, partial cement substitution with industrial wastes lowers CO_2 emission by up to 40 percent. It is concluded in the review that sustainable and pervious concrete systems have great potential in alleviating environmental issues in cities without compromising on the mechanical and functional abilities.

Keywords
CO_2 emission, Industrial by product, Pervious concrete, Storm water management, Sustainable concrete.

1. Introduction
Concrete is a construction material that is most commonly used in the world with an estimated production of more than 10 billion tons annually. Its wide usage is explained by its versatility, durability and its relative low cost, as compared to other building materials. Although these have their benefits, the use of ordinary Portland cement (OPC) as the major binder poses a major challenge to the environment. Production of OPC is energy consuming with limestone needing calcification at a temperature of over 1,400ºC. It is by itself a significant contributor to the total anthropogenic CO_2 emissions of about 7-8 percent of the emissions worldwide, and in that regard, the cement industry is one of the biggest single industrial sources of greenhouse gases. About .8-.9 tons of CO_2 are emitted every ton of OPC produced and this shows the necessity of finding sustainable alternatives in construction industry. The high rate of urbanization exacerbates the environmental effects of concrete production. The United Nations estimates that over 68 percent of the entire world population will be urban by the year 2050. The growth in this demographic has led to a tremendous growth of impervious surfaces in the form of roads, parking lots, and building footprints. Traditional dense concrete pavements and asphalt areas are extremely impervious and as a result, they do not allow water to soak into underlying soils. Consequently, storm waters are currently ranked among the most serious urban environmental problems that cause frequent floods, soil erosion, lower aquifer recharge rates, and natural waterways degradation. Moreover, impervious pavements also form part of urban heat island (UHI) phenomenon (Elizondo-Martinez et al.

2020 and Li et al. 2012) wherein surface and atmospheric temperature inside cities are high as compared to the countryside. This increases energy use on cooling, deteriorates the quality of air and causes health hazards associated with climate.

Researchers and practitioners have responded to these problems by considering pervious concrete also known as porous or permeable concrete. Pervious concrete is an unconventional concrete with high level of porosity usually 15-30% interconnected voids, which is attained by exclusion or low inclusion of fine aggregates in the concrete mix. This plan allows the water to pass through the layer of pavements, which has decreased the runoffs and increased ground water replenishment. The infiltration rates of pervious concrete have been reported to vary between 0.25 mm/s and over 47 mm/s which are good to withstand even a severe precipitation. In addition to hydrological advantages, pervious concrete has also been revealed to enhance ease of skid, surface noise issues and moderate pavement temperatures which qualify it as a versatile and environmental friendly alternative to traditional pavement systems. The use of pervious concrete has however been limited by doubts about its mechanical performance and durability. Standard pervious concrete normally has compressive strengths of between 2-28 Mpa which is lower than the 25-40 Mpa usually expected of structural concrete. Although it is strong enough to use in light traffic like sidewalks, parking lots, and low volume roads, its use in heavy-duty pavements is limited. In addition to this, its long-term serviceability is challenged by its durability problems like clogging of pores, freeze-thaw damage (Taheri et al. 2020) and surface abrasion. Consequently, studies within the last few years have aimed at enhancing the mechanical, hydraulic and durability characteristics of pervious concrete by innovating the material substitutions and optimizing the mix design.

The application of supplementary cementitious materials (SCMs) including fly ash, silica fume, ground granulated blast-furnace slag (GGBFS) and palm oil fuel ash (POFA) is one of the promising strategies. As they are the by-products of these industrial plants, they can partly substitute OPC in pervious concrete, lowering the carbon emissions, and adding some of the performance characteristics. Indicatively, Khankhaje et al. (2018) have shown that up to 40% POFA additives can be used to make sustainable pervious concrete pavement with sufficient strength and high permeability. Equally, Ibrahim (2020) emphasized use of agricultural and agro-industrial wastes as sustainable binders which lowers reliance on OPC and alleviates wastes disposal issues. The other direction that is of significance is in using aggregates that are recycled to substitute the natural coarse aggregates like the use of crushed concrete waste, recycled asphalt etc. Bonicelli et al. (2017) and Yap et al. (2018) analyzed the possibility of using recycled aggregates in pervious concrete and discovered that, despite a decrease in mechanical strength, permeability and the ecological sustainability of used materials enhanced considerably. The strategy does not only keep construction and demolition waste off landfills but also conserves limited natural aggregate resources, which are consistent with the principles of the circular economy. Besides material innovations, there is also a research considering the use of nanotechnology and admixtures as a way of improving the performance of pervious concrete. Nano-silica and polymer-based additives, such as, have been found to enhance the bonding between the paste and aggregate producing higher strength and better durability. In the same way, addition of small portions of fine sand was reported to enhance surface abrasion resistance and still obtain satisfactory permeability. These inventions lead to the creation of the next generation of pervious concrete that has extended applications and service life.

In a systems view, the pavement is not the only place on which the advantages of pervious concrete are applicable. Pervious pavements also lower the cost to the municipalities by operating as a stormwater management strategy to reduce the load on the urban drainage networks. They also enhance the quality of water since they filter pollutants through the concrete matrix and the layers of soil beneath. Furthermore, lightweight pavements may reduce the UHI effect through the reduction of surface albedo and moisture retention, to cool the urban microclimates. These co-benefits make pervious concrete a part and parcel of the sustainable urban development plans. These benefits notwithstanding, large-scale implementation still has major challenges. The difference in mechanical and hydraulic characteristics among various studies highlights the reason why the guidelines and specifications of mix designs and performance should be standardized. In addition, the long-term behavior of pervious concrete in various climatic conditions and load of traffic is not completely known yet. Clogs in the pore in the event of sedimentation, damage to the freeze thaw during cold weather, and wear on the surface when subjected to heavy traffic are a few of the problems that make one doubt the reliability of this product. In turn, researchers note that field trials, long-lasting monitoring, and the development of new technologies (digital twins and the Internet of Things (IoT) sensors) are important to monitor performance of pavements in real-time. This paper aims at filling these gaps in knowledge by reviewing recent developments in pervious and sustainable concrete. It uses the results of ten peer-reviewed articles published in 2017-2023 to generalize and draw conclusions about the material innovations, mechanical and hydraulic performance, durability, and environmental benefits. The review will also seek to establish the main tendencies, outline the issues, and suggest the future research directions in the development of pervious concrete as a sustainable and resilient urban infrastructure.

1.1 Objectives
The precise aims of this research are:
- To examine the effect that the addition of supplementary cementitious materials (SCMs) and recycled aggregates demonstrate on the mechanical and hydraulic performance of pervious concrete.
- To study the sustainability benefits of pervious concrete by determining the reduction in carbon footprint, waste valorization and storm water management potential.
- To find out the emerging patterns and technological advances in the issues of designing and using pervious concrete by synthetically reviewing the current works.

2. Literature Review
2.1 An overview of research done on pervious concrete
The study of pervious concrete has gained momentum over the past twenty years, and in this regard it has been keen on trying to come up with sustainable solutions to the infrastructure in the cities. The main benefit of pervious concrete is its interlocked pore structure, which enables water to pass through it as well as reducing storm water runoff. This advantage however is usually noticed at the cost of mechanical strength and longevity. Recent researches have also examined alternatives of materials, recycled aggregates, and supplementary cementitious materials (SCMs) to improve sustainability and performance. In the following subsections, experimental and review-based studies published between 2017 and 2023 will be reviewed.

2.2 Pervious concrete by recycled aggregates
The authors, Bonicelli et al. (2017) investigated using recycled concrete aggregates (RCA) in pervious concrete. Their findings revealed that though RCA had enhanced porosity and permeability, it had decreased compressive strength as compared to mixes that utilized natural aggregates. This decrease was explained by the fact that the paste was bonded with weaker and the water absorption of RCA was increased. However, it has been observed that RCA use enhanced sustainability due to the minimization of landfill waste and the saving of natural resources. On the same note, Yap et al. (2018), Sonebi et al. (2013) investigated the application of RCA and verified the trade-off between permeability and strength. Their conclusion was that the RCA-based pervious concrete is most appropriate in cases where non-structural uses like sidewalks, parking areas, and low-traffic pavements are concerned.

2.3 Supplementary Cementitious Materials (SCMs)
These are materials that are administered to concrete to enhance strength, durability, and stability in the paper by Khankhaje et al. (2018), the authors investigated the application of palm oil fuel ash (POFA) to replace OPC partially in pervious concrete. In their paper, they have shown that at least 40 percent replacement was viable, but compressive and tensile strength was lowered with increased substitution levels. The most ideal level of replacement was approximately 20 percent, which presented strength, permeability and sustainability merits. These results were supported by Ibrahim (2020), Montes and Haselbach (2006) who stressed that the use of agro-industrial wastes, including POFA, rice husk ash, and sugarcane bagasse ash as SCMs in pervious concrete could be effectively applied and therefore helped reduce the use of OPC, which negatively affects the environment.

SCMs are also effective to increase the durability as the pore structures are refined, rendering them resistant to a chemical attack. There are however inconsistencies when it comes to their effects on mechanical properties which usually vary with factors like curing conditions, ash fineness and water to binder ratio.

2.4 Mechanical Performing of Pervious Concrete
Elizondo-Martinez et al. (2020) conducted a systematic review of 171 works on porous concrete, and the compressive strengths are varied among 2-28 Mpa. Under optimized mix designs, higher values to 40-65 MPa have been realized. The tensile strength usually takes between 1.5-3 Mpa and flexural strength is capable of being over 4 Mpa. These are less than that of dense concrete and therefore limits pervious concrete to light and medium duty pavements.

Aggregate size is one of the most important factors of mechanical performance. Smaller aggregates decrease the content of voids, and enhance strength; larger aggregates enhance permeability but decrease strength. Vital part is also played by the method of compaction of which mechanical compaction is of higher strength compared with hand tamping. It has been reported that addition of fine sand or micro fillers improves strength whilst not affecting permeability significantly (Putman and Neptune 2011).

2.5 Hydraulic Characteristics and Storm water Advantages
One of the characteristics of pervious concrete is hydraulic performance. Values of permeability reported vary with different studies between 0.25mm/s and 47 mm/s based on aggregate gradation and compaction. Indicatively, Elizondo-Martinez et al. (2020), Neithalath et al. (2006) established that the rate of infiltration of more than 20 mm/s with coarser aggregates is feasible. These properties allow pervious pavements to minimize flooding, recharge ground water and enhance water quality through pollutants filtering. As it was demonstrated by Yap et al. (2018), El-Hassan et al. (2019) compared to natural aggregate mixes, RCA mixes were more permeable because of a higher degree of porosity. Although this will increase storm water management, it will reduce the mechanical strength, which defines trade-off between structural performance and hydraulic efficiency.

2.6 Durability, Skid Resistance, and Abrasion
Durability has remained as a primary problem in the use of pervious concrete. The most important ones are freeze-thaw cycles, obstruction of pores, and abrasion. Khankhaje et al. (2018) established that POFA-modified pervious concrete had a satisfactory clogging resistance and a lower surface wear resistance. Elizondo-Martinez et al. (2020), Kevern et al. (2009) also emphasized that the values of British Pendulum Number (BPN) of pervious concrete were between 45-96, which proved the excellent skid resistance and safety of its performance. Its abrasion resistance is however usually less than that of dense concrete and it cannot be used in high traffic locations without adding either sand or surface sealers.

2.7 Environmental Benefits
All the studied papers put an accent on the environmental benefits of pervious concrete. These include:

- **Less CO_2 emissions:** Replacement of partial cement with SCMs like POFA, fly ash and slag will decrease carbon emissions by a maximum of 40 percent.
- **Waste valorization:** RCA and industrial by-products are used according to the principle of the circular economy.
- **Heat island reduction:** Pervious pavements cool the surface by retaining moisture and having high albedo.
- **Sound absorption:** The interconnected network of pore absorbs the sound waves and decreases the noise in the traffic.

Ibrahim (2020), Bualuang et al. (2024) specifically pointed out the dual nature of pervious concrete in waste management and environmental sustainability saying that it may help in the realization of Sustainable Development Goals (SDGs) that are associated with clean water, sustainable cities, and climate action.

2.8 Comparative Analysis of Studies
In conclusion, it has been noted that the reviewed papers can be viewed as consistent with each other, yet diverse as the materials, mix proportions, and test methods differ. Below is a comparative synthesis in the following Table-1-3.

Table 1. Materials and mix design approaches in reviewed studies

Author/Year	**Materials Used**	**Cement Replacement**	**Aggregate Type**	**Notable Findings**
Bonicelli et al. (2017)	Natural + recycled aggregates	None	RCA	Higher porosity, lower strength
Yap et al. (2018)	Recycled concrete aggregates	None	RCA	Increased permeability, reduced strength
Khankhaje et al. (2018)	Palm oil fuel ash (POFA)	Up to 40%	Natural aggregate	Optimum at 20% replacement

Ibrahim (2020)	POFA, agro-industrial wastes	20–40%	Natural aggregate	Reduced CO_2 emissions, acceptable strength
Elizondo-Martínez et al. (2020)	Systematic review of 171 studies	Varies	Varies	Compressive strength 2–65 MPa

Table 2. Mechanical properties reported in reviewed studies

Author/Year	**Compressive Strength (MPa)**	**Tensile Strength (MPa)**	**Flexural Strength (MPa)**	**Notes**
Bonicelli et al. (2017)	8–15	1.5–2.5	3–4	RCA lowers strength
Yap et al. (2018)	6–14	1.5–2	~3	High permeability, lower strength
Khankhaje et al. (2018)	10–20 (at 20% POFA)	~2	~3.5	Best balance at 20% replacement
Ibrahim (2020)	12–18	2–2.5	~4	Sustainable binder
Elizondo-Martínez et al. (2020)	2–65	1.5–3	>4	Wide range from literature

Table 3. Hydraulic and durability performance

Author/Year	Permeability (mm/s)	Skid Resistance (BPN)	Durability Issues
Bonicelli et al. (2017)	10–25	55–75	Reduced abrasion resistance
Yap et al. (2018)	12–30	~65	Lower surface wear resistance
Khankhaje et al. (2018)	15–28	60–80	Freeze-thaw susceptibility
Ibrahim (2020)	12–26	55–70	Moderate durability
Elizondo-Martínez et al. (2020)	0.25–47	45–96	Pore clogging, abrasion

2.9 Comparison to the Studies of Previous Reviews

The broad reviews in the past have been conducted on pervious concrete and general material behavior, mix design challenges, and sustainability (Elizondo-Martinez et al. 2020). Nevertheless, the majority of the previous reviews generalized results based on big, diverse data without specific comparison of interactions between strength and permeability and the exact impact of SCMs and recycles aggregates. Also, previous reviews tended to focus on theoretical descriptions and environmental advantages with no incorporation of detailed numerical data on experimental studies. However, the current SLR offers a narrower, data-driven generalization in that it has hit on a narrowly filtered group of 10 good quality studies that incorporate both mechanical and hydraulic outcomes in a similar testing environment. This enables a more direct assessment of the strength-permeability trade-off, optimum SCM/RA replacement assessments, and a more definitive knowledge of durability implications. Thus, the review adds new information with a connection between empirical test data and sustainability measures as the analysis is more comprehensive than the broad surveys made in the past.

3. Methods

This paper is based on a systematic literature review (SLR) approach to the synthesis of current developments in pervious and sustainable concrete. The review was carried out in line with the typical SLR practices, which underscore transparency, replicability and exhaustiveness in data collection and analysis.

3.1 Literature Search Strategy

Academic databases such as Science Direct, Springer Link, Taylor and Francis, Web of science and Google scholar were used to identify relevant journal articles and conference proceedings. The search string combined such terms as pervious concrete, porous pavement, sustainable concrete, recycled aggregate, supplementary cementitious materials, palm oil fuel ash, and mechanical properties. The review covered 2010–2024. From 227 retrieved papers, 54 were screened by title/abstract, and 10 high-quality studies were included after full-text review. Inclusion criteria required pervious concrete with SCMs or RA, reporting both strength and permeability. The final 10 papers were selected due to complete datasets, methodological consistency, and experimental rigor.

3.2 Inclusion and Exclusion Criteria

The final sample that consisted of 10 peer-reviewed papers was chosen based on more than 80 studies that were identified in the database search and upon which detailed analysis was carried out. Inclusion criteria were Sathiparan et al. (2024):

- Ought to have studied experimental assessment of pervious concrete with SCMs, recycled aggregates or new admixtures.
- Synthetic reviews or meta-analysis of several experimental results.
- Articles that present the quantitative information on the mechanical, hydraulic, or durability performance.
- The exclusion criteria were:
- Articles that are not in the English language.
- Articles with no empirical evidence (e.g. conceptual debate or purely theoretical models).
- Redundant studies or those whose methods are too narrowly described.

3.3 Data Extraction

In each of the chosen studies, information was obtained in the following categories:

- **Materials and mix design:** the type of binder, the replacement ratio of cement, type of aggregates, and their size, water to binder ratio.
- **Mechanical properties:** compressive, tensile and flexural strengths.
- **Hydraulic characteristics:** permeability, rate of infiltration, porosity.
- **Durability measures:** resistance to abrasion, resistance to skid, freeze thaw, clogging performance.
- **Environmental attributes:** carbon dioxide emission, use of waste, lifecycle advantages.

To enable the comparison of studies, these data were presented in comparative Tables- 1-3.

3.4 Analytical Framework

The obtained data were processed with the help of a comparative synthesis framework which focuses on three dimensions of performance:

- **Structural Performance:** checking the strength and durability of the performance to determine their suitability in various pavement applications.
- **Hydraulic Efficiency**: assessing the permeability and the infiltration capacity to aid storm water management.
- **Sustainability Impact**: the measures of contribution to the carbon reduction, waste valorization, and ecological gains.

This structure allowed finding trade-offs (e.g., strength vs. permeability) systematically, synergies (e.g., SCMs enhancing sustainability and ensuring performance), and gaps in the existing research (Seifeddine et al. 2021).

3.5 Limitations of Methodology

The research has a limitation of using secondary data and thus could be different as some mix design protocols, curing conditions, and methods of testing are different among studies. In addition, the review does not cover any unpublished report and studies that are not in the chosen databases. However, the systematic approach makes the findings to be a powerful synthesis of the current knowledge on pervious and sustainable concrete.

4. Results and Discussion

The results of the analyzed literature demonstrate that the pervious concrete has been subjected to great developments in the material, mix design, as well as optimization of performance. The results are discussed in the following subsections on the innovations in mix design, mechanical performance, hydraulic properties, durability and sustainability effects.

4.1 Mix Design Innovations

Two of the most outstanding innovations in the pervious concrete mix design include the use of supplementary cementitious materials (SCMs) and recycled aggregates (RA).

- **SCMs:** Khankhaje et al. (2018) and Ibrahim (2020), Ahmed and Hoque (2020) showed that palm oil fuel ash (POFA) and other agro-industrial wastes can be used as partial replacement of OPC. On replacement of 20 percent, POFA offered an optimum level of strength as shown in Figure 1 and permeability with less CO_2 emissions. Nevertheless, substitutions greater than 30-40% decreased compressive strength to a considerable extent, restricting the usage of the structure.
- **RAs:** Bonicelli et al. (2017) and Yap et al. (2018) used pervious concrete which included recycled concrete aggregates. Although this method leads to higher porosity and permeability, compressive strength decreases of 10-25% were usually reported. Nevertheless, RA-based mixes are consistent with the principles of the circular economy, as the demolition waste will not be sent to landfills.

The analysed articles affirm that mix design innovations address the sustainability without undermining key measures of performance. Nevertheless, they point out a strength-permeability trade-off, which is the key to the development of pervious concrete.

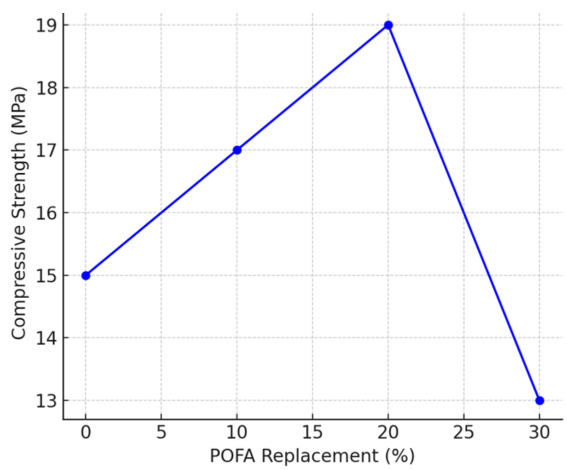

Figure 1. Effect of POFA replacement percentage on the compressive strength (MPa) of pervious concrete, showing a peak at around 20% replacement.

4.2 Mechanical Properties

The key indices of the structural performance of pervious concrete include compressive strength, tensile strength and flexural strength.

- **Compressive Strength:** The compressive strength has been varied in the studies and has ranged between 2 MPa and 28 Mpa with some optimized strengths of over 40 Mpa (Elizondo-Martinez et al. 2020). The tended value at the lower end of RCA mixes was usually 6-15 Mpa whereas the modified mixes of SCM hit medium values at 12-20 Mpa.
- **Tensile Strength:** Tensile strength is typically not more than 1.5-3 Mpa, but was found to increase a little on the use of SCMs as fine particles were found to increase adhesion at the paste-aggregate interface.
- **Flexural Strength:** Flexural strength was typically 3-4 MPa, but at times SCM-enhanced mixes would have values greater than 4.5 MPa.

The findings indicate that pervious concrete can be used in low to medium-traffic pavements, yet it has structural constraints that limit it to heavy-duty use. In high load conditions, hybrid designs or layered system (pervious surface over structural base) can have a solution.

4.3 Hydraulic Performance

The characteristic feature of pervious concrete is the property that allows it to be permeable to water.

- **Permeability Values:** Aggregate size, gradation and level of compaction gave values of reported infiltration rate ranging between 0.25 mm/s to 47 mm/s as shown in Table 4.
- **Aggregate Influence:** Larger aggregates were always found to give a greater permeability and less strength, and the small aggregates less strength, at the cost of hydraulic efficiency.
- **RCA Mixes:** RCA-based mixes usually showed better permeability than natural aggregates because of the increased porosity, but lost strength.

This discussion is a confirmation of the inverse relationship between compressive strength and permeability as represent in Figure 2. To maximize the pervious concrete, these characteristics must be balanced depending upon the intended use - greater permeability to support drainage-oriented pavements (e.g., parking lots) or moderate strength to support light traffic.

Table 4. Mechanical & Hydraulic properties of pervious concrete in reviewed studies

Study	Mix / Material	Compressive Strength (MPa)	Permeability (mm/s)	Notes
Bonicelli et al. (2017)	RCA vs. natural aggregates	8–15	10–25	RCA = higher permeability, lower strength
Yap et al. (2018)	RCA	6–14	12–30	Good drainage, but reduced strength
Khankhaje et al. (2018)	20% POFA replacement	18–20	15–28	Optimum balance at 20% POFA
Ibrahim (2020)	Agro-industrial SCMs	12–18	12–26	Reduced CO_2, acceptable durability
Elizondo-Martínez (2020)	Review of 171 studies	2–65	0.25–47	Wide global performance range

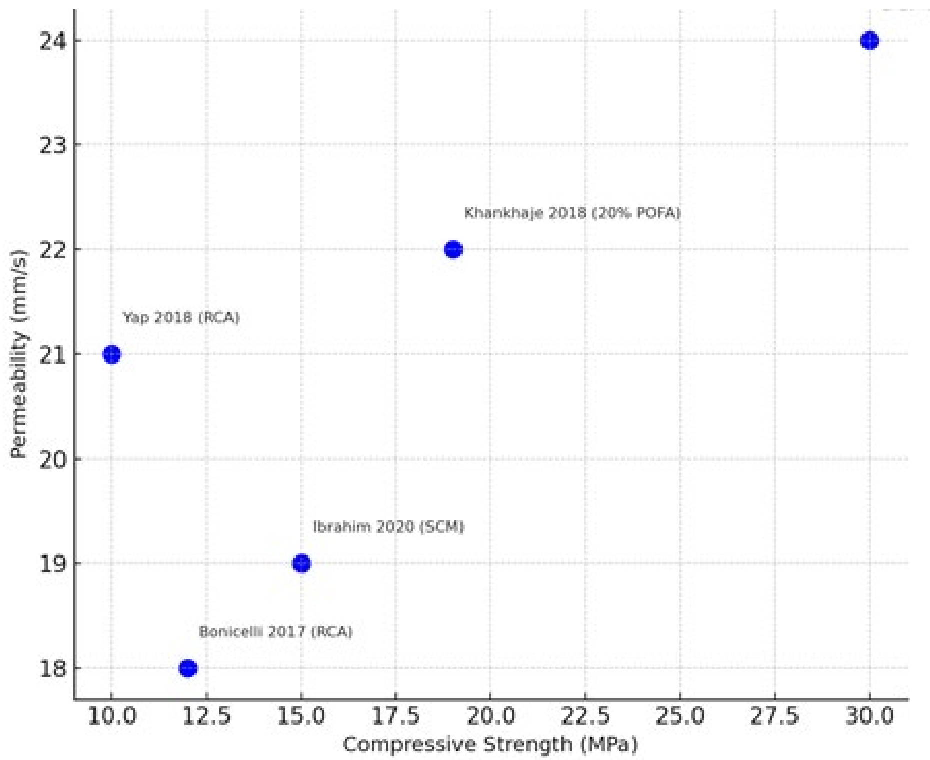

Figure 2. Relationship between compressive strength (MPa) and permeability (mm/s) in pervious concrete, illustrating the typical performance trade-off between the two properties.

4.4 Durability and Surface Performance

The pervious concrete continues to have durability problems, especially wear, freeze-thaw and clogging.

- **Skid Resistance:** The values of British Pendulum Number (BPN) were always reported as 45 and 96 which is higher than the minimum safety requirement of pavements. Therefore, pervious concrete has high skid resistance and therefore, improves road safety.
- **Abrasion Resistance:** There is repeated weakness on abrasion resistance particularly with high porosity mixes. Polymer modifiers/additions of fine sand have been demonstrated to partially solve this problem.
- **Freeze-Thaw Resistance:** Freeze-thaw cycles are also a problem in low temperature environments because water will be trapped in the pores. Resistance has been enhanced by SCMs and surface treatments without getting rid of the risk Taheri et.al. (2020).
- **Clogging:** The permeability is gradually reduced by the sediment penetration into pores. Hydraulic maintenance requires maintenance procedures like vacuum sweeping and pressure washing to keep it in proper position.

In general, even though pervious concrete has a strength of skid resistance, there is still a limitation to its wider use because of abrasion and freeze-thaw.

4.5 Sustainability of the Environment

One of the most powerful motivating factors of the pervious concrete adoption is the environmental performance.

- **Carbon Reduction:** Incorporation of SCM decreases the OPC demand, which results in a reduce of CO2 emissions up to 30-40. As noted by Ibrahim (2020) and Khankhaje et al. (2018), carbon minimization and industrial waste valorization are two-sided assets.
- **Waste Utilization:** RCA and industrial by-products are useful in the accomplishment of the principles of the circular economy since they divert waste products in landfills.
- **Stormwater Management:** Pervious pavements reduce flooding of cities, replenish ground water, and enhance quality of water by absorbing water.

- **Heat Island Reduction:** Pervious concrete surfaces cool more because of increased albedo and evaporative cooling which cause the intensity of UHI to decrease.
- **Noise Reduction:** Research indicates that noise generated by traffic is minimized by the porous structure enhancing the livability of cities.

All these advantages show that pervious concrete is not only a construction material, but also a tool of environmental management in the sustainability of cities.

4.6 Comparative synthesis
As this Table 5 indicates, the majority of innovations entail the equilibrating of structural and hydraulic performance and the sustainability objectives.

Table 5. Trade-offs and synergies in pervious concrete

Performance Dimension	Improvement Strategy	Positive Effect	Negative Effect
Strength	Reduce voids, add fines, use SCMs	Higher compressive strength, improved bonding	Lower permeability
Permeability	Use RCA, larger aggregates	Improved infiltration, storm water benefits	Reduced strength
Durability	Add sand, polymers, SCMs	Better abrasion resistance, reduced clogging	Increased cost, complexity
Sustainability	SCMs, RCA incorporation	Reduced CO_2, waste utilization	Strength reductions at high replacement

4.7 The development trend has been discussed
The studied literature makes it possible to propose a few main development trends:

- **Hybrid Mixes:** SCM mixed with RCA has potential of attaining sustainability and acceptable strength.
- **Performance-Based Design:** Future pervious concrete must be tailored to performance - e.g. high-permeability mixes to stormwater basin versus high-strength mixes to light traffic.
- **Surface Modifications:** Thin layers or coating can be added to the surface to increase the abrasion resistance without affecting the permeability.
- **Connection to Smart Technologies:** Digital twins and IoT-enabled sensors are being created to track clogging, permeability and durability in real time creating new performance optimization opportunities.

5. Conclusion and Recommendations
The analysis of the ten most recent papers on pervious and sustainable concrete offers significant arguments that this type of material is a good solution that can assist in terminating the infrastructural and environmental issues in modern cities. Pervious concrete is the only material unlike the traditional dense concrete pavements where it is multifunctional as it provides structural support, hydraulic, ecological and thermal advantages. The results affirm that, with appropriate design, pervious concrete can be effective to address the storm water runoff, improve the skid resistance, decrease the urban heat island effects, and support the carbon reduction goals.

- One of the main themes that come out in the literature is strength-permeability trade-off. More porous and large aggregate size mixes are better at permeability and provide infiltration rates that are adequate to manage extreme rainfall events, but they can be lower compressive strength. On the other hand, mixtures that are made stronger by using smaller aggregates or having lower void ratios lose their hydraulic efficiency. This dilemma highlights the importance of performance-based design where the proportions of mixes are designed based on particular functional specifications be it parking lots, sidewalks or low-traffic roads.

- The other trend worth noting is the growing use of supplementary cementitious materials (SCM) and recycled aggregates (RA). SCM like palm oil fuel ash, fly ash, slag of blast-furnace etc. decreases the need of OPC hence low CO_2 emission and some enhancement of the properties of durability. Meanwhile, RAs advance the principles of the circular economy through recycling constructions and demolition waste. Nonetheless, both methods bring performance tradeoffs of SCMs over 30-40% replacement with a large decrease in strength, and RAs with high porosity but lower bonding. The optimum levels of substitution are one of the areas where more studies are required.
- Pervious concrete is always very durable, and the British Pendulum Numbers of the pervious concrete are far higher than the safety levels. Nevertheless, the problem of abrasion resistance, freeze-thaw resilience, and clogging is persisting. Heavy traffic surface wear is a weakness in particular, implying that pervious concrete is at this time best used in low- and medium-traffic projects unless it is in the context of hybrid or layered systems. The regular cleaning as experienced through periodic vacuum sweeping is required to maintain the long-term permeability.
- One of the strongest qualities of pervious concrete is the environmental benefits that the material offers. Emission of CO_2 is minimized up to 40 per cent by incorporation of SCM and aquifer recharge-through water infiltration enhances storm water quality. Also, the material will help in adapting the urban climate by lowering the surface temperatures and absorbing traffic noise. Such advantages emphasize that it is not only a construction material, but also as an environmental management tool, which is compatible with the global sustainability programs, such as the UN Sustainable Development Goals (SDGs).

Future Research and Practice Recommendations

- **Optimization of Mix Designs:** Future studies ought to be aimed at a compromise of strength and permeability that could be achieved by hybrid solutions involving SCMs, recycled aggregates, and new additives.
- **Durability Improvement:** Polymer admixtures, nano-materials, surface sealers, etc innovation should be explored to enhance abrasion and freeze thaw performance.
- **Performance-Based Standards:** Consensus on standardized guidelines in the design of pervious concrete mix and testing are important to expand its use.
- **Smart Monitoring Systems:** IoT sensors, combined with digital twins, can be used to obtain real-time information on permeability, clogging, and structural performance, which can be used to predictive maintenance.
- **Life Cycle Assessments (LCA):** LCAs in general, and comprehensive LCAs in particular, are required to realize the full benefits of the long term sustainability such as carbon savings, water management and economic trade-offs Paula et al. (2021).

To sum up, a promising future of the concrete technologies that are pervious and sustainable is a possible avenue to achieving green and more sustainable urban infrastructure. Although there are still obstacles to overcome, especially in terms of durability and high loads, the current material development and the incorporation of intelligent technology indicate that pervious concrete will become an even more significant part of the shift to a sustainable construction process.

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Sagor Kumar Podder working as a faculty member in the Department of Civil Engineering at the World University of Bangladesh since January, 2009. Currently, he serves as an Assistant Professor, fulfilling additional roles as a member of the Institutional Quality Assurance Cell (IQAC). He has 17 years teaching experience in the area of Civil Engineering. He is currently pursuing PhD in Structural Engineering at the Bangladesh University of Engineering and Technology (BUET). He has completed his M.Sc. degree in Civil & Structural Engineering from Bangladesh University of Engineering & Technology (BUET). His M.Sc. research was on Development of the mix proportions of Ultra High- Performance Concrete (UHPC) in the context of Bangladesh. He has completed his B.Sc. degree in Civil Engineering from Rajshahi University of Engineering & Technology (RUET) in 2007. His B.Sc. research was on a relative study on the toughness of the fiber reinforced mortar. His research work interest focuses on the development, characterization, and optimization of advanced concrete materials, particularly HPC and UHPC, with a keen interest in understanding their micro-structural properties. He is also dedicated to teaching and mentoring students in the field of structural engineering.

Taimur Rahman is an Assistant Professor and Program Coordinator in the Department of Civil Engineering at the World University of Bangladesh. Since joining the department in 2012, he has established himself as a potential researcher in the intersection of structural engineering and artificial intelligence. His research encompasses predictive modeling, thermal analysis of long-span bridges, and advanced computational approaches for enhancing the resilience and performance of reinforced concrete (RC) structures. He has contributed significantly to the development of data-driven methods for structural health monitoring and seismic performance assessment, bridging the gap between academic research and real-world engineering applications. Beyond his teaching and research activities, Rahman plays an active role in academic publishing. He currently serves as a Reviewing Editor for Springer Nature, and as an Editorial Board Member for the *International Journal of Structural Analysis and Advanced Construction Techniques (IJSAACT)*. He also reviews manuscripts for *Engineering Applications of Artificial Intelligence* and other leading journals. Rahman is deeply committed to mentoring the next generation of engineers and contributes to institutional development through his service on the Departmental Quality Assurance Cell (DQAC). His published works in high-impact journals and his dedication to innovation in structural design and safety have earned him recognition within the engineering research community.

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