Sustainable Pavement Drainage Systems (SPDS): A Solution for Rainwater Runoff Mitigation in Urban Areas

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Abstract. The increasing frequency of extreme weather events and urbanization have exacerbated rainwater runoff, posing significant threats to urban infrastructure and the environment. In response to the United Nations' Sustainable Development Goals (SDGs), this study proposes the implementation of Sustainable Pavement Drainage Systems (SPDS) as a viable solution for rainwater runoff management in urban areas. SPDS integrates eco-friendly materials and designs to reduce stormwater runoff, alleviate drainage congestion, and mitigate the environmental impacts of urbanization. A case study in Palembang city, Indonesia, demonstrates the effectiveness of SPDS in decreasing surface discharge, improving pavement durability, and enhancing water conservation. The results of this research have significant implications for urban planners, policymakers, and infrastructure developers seeking sustainable and resilient solutions to rainwater runoff challenges.

Keywords: Sustainable Pavement Drainage Systems, Rainwater Runoff, Urbanization, Climate Change, Water Conservation, Environmental Sustainability.

1 Introduction

1.1 Background

In 2015, the United Nations adopted the Sustainable Development Goals (SDGs) as a 2030 agenda. Its execution underscores the importance of biodiversity, water conservation, climate change, and environmental contamination. Climate change has resulted in the alteration of rainfall patterns, the initiation of extreme weather events such as hurricanes and floods, and the elevation of sea levels. Uncontrolled surface discharge can accumulate and overpower drainage, thereby altering the moisture content of pavements during periods of heavy rainfall. The expansion of urban settlements, such as Palembang city, leads to a decrease in the area of rainwater catchment areas as a result of the increased coverage of pavement. This, in turn, results in a significantly shorter period of time for water to accumulate, causing the accumulated rainwater to exceed the capacity of the existing drainage system. This is frequently demonstrated by the discharge of water from drainage channels at numerous locations

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throughout the city, with a particular emphasis on settlements. Making Permeable Pavement such as Porous Concrete (PC) is an attempt to decrease the surface dis- charge of precipitation and increase infiltration into the soil. PC is concrete with a special form of concrete designed to facilitate water permeability, which is different from conventional paving materials. The material possesses a continuous void volume ranging from 15% to 25%, extensively incorporates coarse aggregates, and utilizes minimal or no fine aggregates (E et al., 2021).

In addition, PCs outlast conventional drainage systems and are more cost-effective (Mohamed Ahmad et al., 2019). A PC may function as an irrigation system as well (Javaheri-Tehrani et al., 2020). Additionally, by modifying the earth's temperature and humidity, the use of PC in concrete applications greatly lowers the creation of urban heat islands (Chen et al., 2019; Elizondo-Martínez, Andrés-Valeri, Jato-Espino, et al., 2020). Currently, PC is extensively utilized in sidewalks, pedestrian pathways, bicycle lanes, parking areas, rain gardens, hydraulic constructions, slope stabilization, spurs, and coastal barriers (Elizondo-Martínez, Andrés-Valeri, Rodríguez-Hernández, et al., 2020; Indhu et al., 2021).

Nonetheless, similar to conventional concrete manufacturing, Portland cement serves primarily as the binding agent in PC synthesis. Approximately 5–7% of world-wide carbon dioxide (CO2) emissions stem from cement manufacturing (Benhelal et al., 2013), with around 0.9 tons of CO2 emitted each ton of cement produced (Mahasenan et al., 2003). Carbon dioxide is a significant greenhouse gas that amplifies the carbon footprint and contributes to global warming. Given the escalating signifi- cance of global warming and climate change, it has become imperative to implement substantial new measures.

In this context, identifying lasting solutions to lower CO2 emissions from cement production has become essential for sustainability. Utilizing waste industrial materials like fly ash (FA) and bottom ash (BA) as substitutes for Portland cement and fine aggregate in concrete production represents a significant limitation associated with the use of Portland cement and natural sand. FA comprises extremely fine particles that are captured by electro filters at the chimney exits, resulting from the combustion of low-calorie powdered coal in the electricity generation process at thermal power plants. The ashes in the artificial pozzolanic category, characterized by their volatility and fine-grained nature, arise as waste material and are classified into two categories: F- and C-classes (Kumar et al., 2022). FA and BA are a byproduct of industrial pro- cesses and are associated with significant recycling expenses.

FA and BA have significant pozzolanic activity due to its chemical composition, which includes amorphous silica (SiO2). These qualities allow them to generate C-S-H structures by interacting with portlandite (CH) produced during cement hydration (Li et al., 2023; Wiranata et al., 2022). This allows concrete containing FA and BA additives to obtain increased strength. However, due to delayed hydration in FA-BA added concretes, later-age strengths are greater than early-age strengths (Sereewatthanawut et al., 2023; Wiranata et al., 2022).

Numerous studies investigate the strength and durability characteristics of concretes incorporating FA (Hwang &Moreno Cortés, 2021; Nazeer et al., 2023). According to Singh et al. (Singh et al., 2022), a 3.1% improvement in 90-day compressive strength was seen when FA was employed at a rate of 20% by weight instead of cement. They also showed that when FA concentrations rose, so did porosity and permeability. The compressive strengths after 7 days and 28 days were found to be 2.5% and 4% lower, respectively, when FA was replaced with cement at a weight ratio of 10% by Nazeer et al., 2023.

On the other hand, studies have have found that incorporating bottom ash can significantly influence the mechanical properties of concrete. For instance, a study found that concrete mixtures with up to 30% bottom ash replacement maintained comparable compressive strength to conventional concrete, suggesting that bottom ash can effectively serve as a lightweight aggregate, enhancing overall performance without compromising structural integrity (Poudel et al., 2024).

In addition to mechanical strength, the durability of bottom ash concrete has been a focal point of research. Investigations have shown that concrete with bottom ash exhibits improved resistance to chemical attacks, such as sulfate and chloride exposure. A comprehensive life cycle assessment highlighted that utilizing bottom ash not only diminishes the carbon footprint of concrete production but also promotes a circular economy. This approach aligns with the growing need for sustainable construction practices, making bottom ash a promising material for future concrete applications (Mohammed et al., 2021; Wiranata et al., 2022).

The environmental benefits of using bottom ash in concrete are also noteworthy. By substituting natural sand with this industrial byproduct, the construction industry can reduce landfill waste and conserve natural resources. A comprehensive life cycle assessment highlighted that utilizing bottom ash not only diminishes the carbon footprint of concrete production but also promotes a circular economy. This approach aligns with the growing need for sustainable construction practices, making bottom ash a promising material for future concrete applications (Karalar et al., 2022).

However, challenges remain in the widespread adoption of BA in porous concrete. Variability in the quality and properties of bottom ash, influenced by its source and combustion conditions, can affect the consistency of PC performance. Additionally, regulatory hurdles often complicate the use of industrial byproducts in construction. Ongoing research is essential to establish standardized practices and ensure the reliable application of bottom ash in PC, paving the way for its integration into mainstream construction product.

1.2 Objective

Therefore, research was proposed to provide a solution to storm water runoff called sustainable pavement drainage systems (SPDS) by investigating the feasibility of utilizing fly ash (FA) as a partial replacement for cement and bottom ash as a substitute for fine aggregate (natural sand) in porous concrete. This study aims to evaluate the impact of varying percentages of FA (10%, 20%, and 30% by weight of cement) and bottom ash (50%, 75%, and 100% by weight of fine aggregate) on the mechanical properties of compressive and flexural strengths. In addition, porosity was also analyzed to understand how these substitutions affect overall performance.

2 Materials and methods

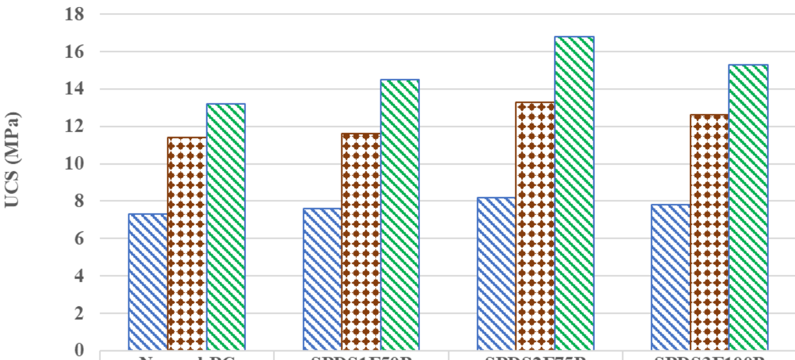
The gradation of coarse aggregates used in these study ranges from retained size 4.75mm up to 19mm, according to size number 67 as per ASTM C33/C33M , as seen in Fig. 1. Conversely, the gradation of fine aggregate adheres to the ASTM C33/ C33M specifications between the sizes of 0.15mm to 2.36mm. In addition, four sam- ples were prepared using varying percentages of FA and BA to evaluate their effects on mechanical properties, specifically compressive and flexural strengths. FA was incorporated at three different levels: 10%, 20%, and 30% by weight of cement. Con - currently, BA was used as a replacement for fine aggregate at proportions of 50%, 75%, and 100% by weight, as shown in Table 1. The mixing process involved thor- oughly blending the aggregates, cement, and water, followed by casting the mixtures into standardized molds. After curing for 28 days, the mechanical properties were assessed through standard testing methods for both compressive and flexural strengths. Additionally, porosity analysis was conducted to determine how the vary- ing substitutions of FA and bottom ash influenced the overall performance and func - tionality of the SPDS mixes as porous concrete. The results aimed to establish a corre- lation between the material composition and the resulting mechanical characteristics, facilitating a deeper understanding of the implications of using industrial by-products in concrete formulations.

3 Results and discussion

3.1 Compressive strength

Unconfined Compressive Strength (UCS) results for the various mixes of porous concrete reveals critical insights into their mechanical performance over time. At the 7-day mark, all mixes achieve a minimum UCS of 7.3 Mpa (as seen in figure 1), which is indicative of adequate early strength necessary for initial load-bearing appli- cations. Among these, SPDS2F75B demonstrates the highest early strength at 8.2 MPa, suggesting that its specific formulation is likely characterized by optimal aggre- gate and binder ratios facilitates superior hydration and strength development in the initial curing phase. As the concrete matures to 14 days, notable strength increases are observed across all mixes, with SPDS2F75B again leading at 13.3 MPa. This increase signifies effective cement hydration and the formation of a robust microstructure, essential for ensuring durability and long-term performance. The other mixes, while displaying strength gains, do not match the performance of SPDS2F75B, indicating potential areas for optimization in their formulations. By 28 days, the UCS values peak across all mixes, with SPDS2F75B achieving a remarkable 16.8 MPa. This strength not only highlights its excellent performance but also suggests that the mix can withstand considerable loads, making it suitable for applications where structural integrity is paramount. In contrast, the other mixes, such as SPDS1F50B and SPDS3F100B, exhibit commendable strengths of 14.5 MPa and 15.3 MPa, respec- tively, yet they still fall short of the optimal performance displayed by SPDS2F75B.

The overall trend indicates that while all tested mixes of porous concrete exhibit promising strength characteristics, the superior performance of SPDS2F75B positions it as the most effective option for applications requiring both strength and permeability. This is particularly relevant in contexts such as permeable pavements and drainage systems, where the ability to handle hydraulic loads, coupled with mechani- cal strength, is essential. Further investigations into the durability, resistance to environmental factors, and long-term stability of these mixes would provide a comprehensive understanding of their suitability in real-world applications.



	Normal-PC	SPDS1F50B	SPDS2F75B	SPDS3F100B
7-d (MPa)	7.3	7.6	8.2	7.8
14-d (MPa)	11.4	11.6	13.3	12.6
28-d (MPa)	13.2	14.5	16.8	15.3

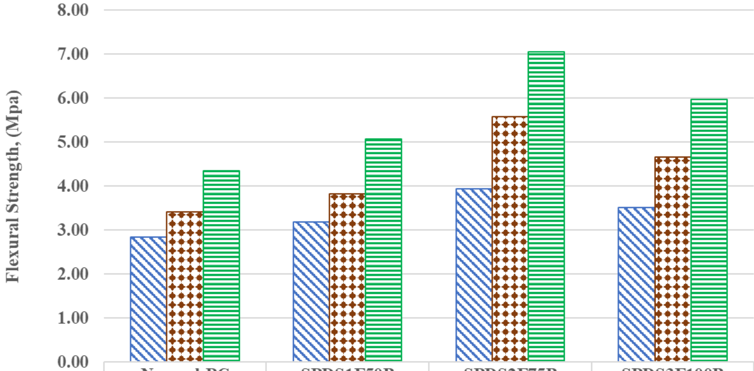
Fig. 1. UCS testing results.

3.2 Flexural strength

Flexural Strength (FS) results for the various mixes of porous concrete reveal important insights into their structural performance under bending loads, which is criti - cal for applications such as pavements and slabs. At 7 days, the FS values indicate a modest level of early strength, with Normal-PC achieving the lowest flexural strength at 2.8 MPa. In contrast, SPDS2F75B exhibits the highest early flexural strength at 3.9 MPa, suggesting that this mix is likely to incorporate a more effective combination of materials or additives that enhance the concrete's ability to resist bending forces early in the curing process.

As the curing period progresses to 14 days, all mixes demonstrate notable increases in flexural strength, with SPDS2F75B leading again at 5.6 MPa. This significant rise highlights the mix's superior hydration characteristics and microstructural development, which are essential for improving the concrete's performance under tensile stresses. Other mixes, such as SPDS1F50B and SPDS3F100B, show moderate increases, indicating they may possess less efficient hydration or suboptimal material compositions for flexural performance.By 28 days, the FS values peak, with SPDS2F75B reaching 7.1 MPa, reinforcing its position as the most effective mix for applications requiring enhanced flexural performance. The other mixes, while also improving—SPDS1F50B at 5.1 MPa and SPDS3F100B at 6.0 MPa—still fall short of the strength exhibited by SPDS2F75B. This trend underscores the importance of mixed design in achieving the desired balance of strength and permeability in porous concrete.

The results suggest that while all mixes exhibit some degree of flexural strength, the superior performance of SPDS2F75B indicates its potential for applications where resistance to bending is critical, such as in structural elements that must support dy - namic loads. The generally lower flexural strength values across all mixes highlight a potential limitation for porous concrete in scenarios where high tensile stresses are expected, necessitating careful consideration of design and application contexts. Future research should focus on optimizing these mixes further, potentially through the incorporation of fibers or other additives, to enhance flexural strength and overall durability, ensuring they can meet the demands of various engineering applications while maintaining their permeability benefits.



	Normal-PC	SPDS1F50B	SPDS2F75B	SPDS3F100B
7-d (MPa)	2.8	3.2	3.9	3.5
14-d (MPa)	3.4	3.8	5.6	4.7
28-d (MPa)	4.4	5.1	7.1	6.0

Fig. 2 Flexural strength testing results.

3.3 Porosity

Porosity results for the various mixes of porous concrete provide critical insights into their structural and functional characteristics. At 7 days, Normal-PC exhibits the highest porosity at 21.5%, indicating a more porous structure that enhances water drainage capabilities. However, this increased porosity may also raise concerns re- garding the material's mechanical strength, as excessive voids can compromise load- bearing capacity. In comparison, the SPDS mixes demonstrate lower porosity levels, with SPDS2F75B at 18.7%, suggesting a denser composition that likely contributes to greater structural integrity while still allowing for sufficient permeability.

As the curing period progresses to 14 days, a slight reduction in porosity is ob- served across all mixes, indicative of ongoing hydration and densification of the con- crete matrix. Normal-PC maintains the highest porosity at 21.1%, while SPDS2F75B continues to show the lowest porosity at 18.2%. This trend suggests that the design of the SPDS mixes may effectively optimize particle packing and minimize voids, resulting in a more robust structure.

By 28 days, porosity values stabilize, with Normal-PC at 21.0% and SPDS2F75B at 18.1%. The consistently lower porosity of the SPDS mixes underscores their poten- tial advantages for applications requiring both strength and effective drainage, such as permeable pavements and environmental management systems. Overall, the results indicate a favorable balance in the SPDS mixes between porosity and mechanical performance, highlighting their suitability for environments where both structural integrity and water management are essential. Future research could focus on refining these mixes to optimize the trade-off between porosity, permeability, and strength for enhanced performance in various engineering applications.

4 Conclusion

The comprehensive analysis of the Unconfined Compressive Strength (UCS), Flexural Strength (FS), and porosity results for various mixes of porous concrete reveals critical insights into their mechanical performance and suitability for practical applications. SPDS2F75B consistently outperforms the other mixes at all testing intervals, achieving the highest UCS and FS values, indicating its superior formulation and effective hydration characteristics. This mix demonstrates remarkable strength, making it ideal for applications that demand both structural integrity and permeability, such as permeable pavements and drainage systems.

In contrast, while Normal-PC exhibits the highest porosity, this attribute raises concerns about its mechanical strength, suggesting a trade-off between drainage capacity and load-bearing ability. The SPDS mixes, particularly SPDS2F75B, show a favor- able balance of lower porosity and enhanced mechanical properties, indicating their potential for environments requiring efficient water management without sacrificing structural performance.

The observed trends highlight the importance of mix design in achieving optimal strength and durability while maintaining permeability. Future research should focus on further optimizing these mixes, possibly through the incorporation of additives or fibers, to enhance flexural strength and overall durability. This approach will ensure that porous concrete can meet the diverse demands of modern engineering applications, providing effective solutions for both structural integrity and environmental sustainability.

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