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Enhancing Mechanical and Hydraulic Properties of Fiber-Reinforced Pervious Concrete Using Recycled Aggregates for Sustainable Urban Infrastructure

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Abstract

This study investigates the mechanical, hydraulic, and durability properties of pervious concrete incorporating natural fine aggregates (NFCA), recycled coarse aggregates (RCA), and synthetic fibers (polyethylene, polypropylene, and nylon). The research aims to optimize the performance of pervious concrete for sustainable urban infrastructure while maintaining adequate strength and permeability. Experimental evaluations focused on compressive strength, split tensile strength, flexural strength, impact resistance, permeability, and porosity. Results demonstrated that NFCA-based mixes improved in strength due to enhanced particle packing, while RCA-based mixes, despite challenges with adhered mortar, achieved significant strength gains with fiber reinforcement. Among the fiber types tested, nylon fibers exhibited superior performance, achieving the highest compressive strength of 23.97 MPa and impact resistance of 70.4 MPa at 20% fiber content—representing a 34.6% improvement over baseline values. The incorporation of synthetic fibers enhanced crack resistance, stress distribution, and toughness, making RCA-based pervious concrete a viable alternative to conventional concrete. Additionally, permeability values ranged between 15 mm/s and 19 mm/s, ensuring efficient stormwater infiltration while maintaining sufficient structural integrity. Predictive models such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), and Multiple Linear Regression (MLR) were employed to validate experimental findings, demonstrating high accuracy in predicting mechanical properties. The study confirms that fiber-reinforced RCA-based pervious concrete is a sustainable, durable, and functional material for urban infrastructure applications, offering an eco-friendly solution for pavements, sidewalks, and stormwater management systems.

Keywords:

Pervious concrete, recycled coarse aggregates, synthetic fibers, compressive strength, impact resistance, permeability, predictive modeling

Introduction

Urban infrastructure development faces increasing challenges due to population growth, urbanization, and climate change (Haselbach, 2010). Conventional construction materials often fail to address critical concerns such as stormwater management, environmental sustainability, and long-term durability (Schaefer et al., 2006). Pervious concrete has emerged as an innovative solution, providing a unique combination of load-bearing capacity and permeability (Tennis et al., 2004). By allowing water to infiltrate through its structure, pervious concrete mitigates urban flooding, enhances groundwater recharge, and reduces the heat island effect (Yang & Jiang, 2003). The primary components of pervious concrete include coarse aggregates, cement, and water, with minimal or no fine aggregates, creating an interconnected void structure that promotes water infiltration (Li et al., 2014). However, the absence of fine aggregates often results in reduced mechanical strength and durability (Montes & Haselbach, 2006). Researchers have addressed these limitations by incorporating recycled coarse aggregates (RCA) and synthetic fiber reinforcements, aiming to improve the structural and functional properties of pervious concrete while enhancing sustainability (Kevern et al., 2009). Recycled coarse aggregates (RCA) derived from construction and demolition waste serve as an eco-friendly alternative to natural aggregates, reducing the demand for virgin materials and minimizing waste (Mehta & Monteiro, 2014). The incorporation of RCA aligns with circular economy principles, promoting sustainability in infrastructure development (McCain & Dewoolkar, 2010). However, RCA often exhibits higher porosity, lower density, and weaker interfacial bonding, which can negatively impact concrete performance (Rangelov et al., 2020). To counteract these drawbacks, supplementary materials such as fibers have been introduced (Kumar et al., 2021).

Synthetic fibers, including polyethylene, polypropylene, and nylon, have gained attention for their ability to enhance mechanical properties, improve tensile strength, and increase impact resistance (Li et al., 2014). Among these, nylon fibers have demonstrated superior tensile strength and stress distribution within the concrete matrix, enhancing crack-bridging capabilities and overall durability (Wang et al., 2016). The combination of RCA and synthetic fibers allows for an optimal balance between mechanical strength, permeability, and environmental sustainability (Montes & Haselbach, 2006). A key property of pervious concrete is its hydraulic performance, which is dictated by permeability and porosity (Schaefer et al., 2006). Proper void structure is essential to achieve efficient water infiltration without compromising strength (Tennis et al., 2004). Researchers emphasize that curing conditions and compaction techniques play a critical role in balancing permeability and structural integrity (Yang & Jiang, 2003).

Advancements in predictive modeling techniques, such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), and Multiple Linear Regression (MLR), have enabled accurate optimization of pervious concrete mix designs (Mehta & Monteiro, 2014). These models help establish relationships between material properties, mix proportions, and performance metrics (Rangelov et al., 2020). By leveraging machine learning and statistical tools, researchers can develop tailored pervious concrete solutions that meet the growing demands of modern urban infrastructure (Kumar et al., 2021). The significance of this study lies in its comprehensive evaluation of NFCA- and RCA-based pervious concrete, reinforced with synthetic fibers (Wang et al., 2016). This research not only examines the mechanical and hydraulic properties of the material but also explores its potential for sustainable construction (McCain & Dewoolkar, 2010). By integrating advanced experimental techniques and predictive modeling, this study provides a holistic understanding of pervious concrete's performance in urban environments (Kevern et al., 2009). The growing need for sustainable and resilient infrastructure underscores the importance of innovative materials likes pervious concrete (Mehta & Monteiro, 2014). This study contributes to the field by demonstrating how material modifications can improve the strength, durability, and permeability of pervious concrete while maintaining sustainability (Rangelov et al., 2020). The findings have important implications for urban planners, engineers, and policymakers seeking eco-friendly alternatives for modern infrastructure development (Kumar et al., 2021).

Methodology

The methodology employed in this study encompasses a combination of material preparation, experimental testing, and predictive modeling to evaluate the mechanical and hydraulic properties of pervious concrete. The primary components used include natural fine aggregates (NFCA), recycled coarse aggregates (RCA), and synthetic fibers (polyethylene, polypropylene, and nylon), with variations in fiber content ranging from 0% to 20%.

1. Material Preparation

Aggregate Selection:

- Natural Fine Coarse Aggregates (NFCA): Sourced from local quarries, ensuring uniformity in grading and quality.
- Recycled Coarse Aggregates (RCA): Processed from construction and demolition waste, sieved to remove impurities, and graded to meet design specifications.

Synthetic Fibers:

- Polyethylene, polypropylene, and nylon fibers were selected based on their tensile strength, elasticity, and compatibility with concrete.
- Fiber dosages of 0%, 5%, 10%, 15%, and 20% were incorporated into the mixes to assess their influence on mechanical and hydraulic properties.

Mix Design:

- A standard water-to-cement (w/c) ratio of 0.35 was maintained for all mixes to ensure consistent hydration.
- The mix proportions were adjusted to balance strength and permeability while minimizing void content, ensuring an optimal combination of mechanical performance and hydraulic efficiency.

2. Experimental Testing

To comprehensively assess the mechanical and hydraulic properties of pervious concrete, a series of standardized tests were conducted following ASTM guidelines.

Compressive Strength Testing:

- Specimens: Cylindrical samples (150 mm diameter × 300 mm height) were cast and tested at 7 and 28 days.
- Testing Standard: Conducted as per ASTM C39, using a universal testing machine to determine load-bearing capacity and failure mechanisms.

Split Tensile Strength Testing:

- Specimens: Disc-shaped samples (150 mm diameter × 50 mm height) were used.
- Testing Standard: Adhered to ASTM C496 to assess resistance to tensile cracking under loading.

Flexural Strength Testing:

- Specimens: Beam samples (100 mm × 100 mm × 500 mm) were prepared.
- Testing Standard: Conducted following ASTM C78 using third-point loading to measure flexural performance and fiber reinforcement's crack-bridging capabilities.

Impact Resistance:

- Drop-weight impact tests were performed on disc-shaped specimens to evaluate resistance to dynamic loading.
- Recorded Data: The number of blows required to produce the first crack and ultimate failure.

Hydraulic Properties Testing:

- Permeability Measurement: Falling head permeability tests were conducted to determine infiltration rates (mm/s).
- Porosity Determination: Void content was calculated as a percentage of the total specimen volume to quantify porosity variations.

3. Predictive Modeling

To improve the accuracy and reliability of performance predictions, various statistical and machine learning models were implemented.

Artificial Neural Networks (ANN):

- A multilayer perceptron (MLP) model was developed to predict compressive strength and permeability.
- Input parameters included fiber type, fiber dosage, aggregate type, and curing age.
- Training and Validation: The model was trained on 80% of the experimental data and validated using the remaining 20%, ensuring robust predictions.

Support Vector Machines (SVM):

- Regression models were applied to optimize mix designs and predict mechanical and hydraulic properties.
- SVM effectively captured nonlinear relationships, making it a valuable tool for generalizing mix design performance across different compositions.

Multiple Linear Regression (MLR):

- MLR models were employed to establish relationships between mix proportions and performance outcomes.
- Although simpler than machine learning approaches, MLR provided insightful correlations between w/c ratio, density, permeability, and strength characteristics.

4. Statistical Analysis

To ensure the reliability and reproducibility of the results, a detailed statistical analysis was conducted on experimental data.

- Coefficient of Determination (R^2): Used to assess model accuracy, indicating the proportion of variance explained by the independent variables.
- Root Mean Square Error (RMSE): Evaluated prediction errors, ensuring minimal deviations from experimental results.
- Mean Absolute Percentage Error (MAPE): Measured the percentage deviation between predicted and experimental values.
- Significance Testing: Statistical tests (e.g., ANOVA) were applied to verify the influence of different variables on strength and permeability.

This comprehensive methodology enabled the systematic evaluation of NFCA and RCA-based pervious concrete, highlighting the influence of synthetic fibers on both mechanical and hydraulic properties. By integrating experimental testing with advanced modeling techniques, the study provides actionable insights for optimizing mix designs and promoting sustainable construction practices. The use of machine learning models such as ANN and SVM allows for enhanced predictive accuracy, ensuring efficient mix optimization and performance evaluation. Through these approaches, the study contributes valuable knowledge to the field of pervious concrete, particularly in enhancing durability and sustainability through fiber reinforcement and optimized aggregate selection.

Results

Compressive Strength

The compressive strength of pervious concrete mixes varied significantly based on the type of aggregate, fiber content and curing conditions. The results demonstrated that fine aggregate replacement and fiber reinforcement played crucial roles in improving the load-bearing capacity of the material.

For mixes incorporating natural fine aggregates (NFCA), the compressive strength increased from 11.35 MPa at 0% fine aggregate replacement to 20.03 MPa at 20% replacement. This improvement was primarily due to enhanced particle packing, which contributed to a denser matrix and better load distribution. The gradual improvement in compressive strength suggests that an optimal level of fine aggregate replacement enhances overall performance without significantly compromising permeability.

In contrast, recycled coarse aggregate (RCA) mixes exhibited slightly different trends. At 20% replacement, the compressive strength reached 19.23 MPa, indicating a 138% increase compared to the baseline values. The enhancement in RCA-based mixes can be attributed to the improved compaction techniques and the effectiveness of curing, which helped mitigate the weaker interfacial transition zones (ITZ) typically found in RCA.

The most notable improvement in compressive strength was observed in fiber-reinforced RCA mixes. Among the different fiber types tested, polyethylene fibers increased compressive strength to 23.87 MPa, while polypropylene and nylon fibers achieved 21.13 MPa and 23.97 MPa, respectively. The superior performance of nylon fibers suggests that their higher tensile strength and ability to distribute stress efficiently played a crucial role in increasing the overall load-bearing capacity. These findings indicate that incorporating synthetic fibers not only enhances strength but also reduces brittleness, making pervious concrete more durable for structural applications.

Split Tensile Strength

Split tensile strength tests highlighted the brittle nature of pervious concrete and demonstrated the positive impact of fiber reinforcement in improving crack resistance and tensile performance.

For NFCA-based mixes, the split tensile strength increased from 0.90 MPa at 0% fine aggregate replacement to 1.73 MPa at 20% replacement. This increase suggests that optimizing the mix design enhances matrix cohesion, reducing the likelihood of premature failure under tensile loading.

The most significant improvements were observed in RCA-based mixes reinforced with nylon fibers. At 20% fiber content, the split tensile strength peaked at 2.73 MPa, marking a 50% improvement over the baseline. The increase in tensile strength can be attributed to the fibers' ability to bridge cracks, distribute stress more effectively, and enhance post-cracking ductility. The superior performance of nylon fibers, in particular, suggests that their elasticity and bonding capacity contribute to greater resistance against tensile forces. These results confirm that incorporating synthetic fibers into pervious concrete enhances its overall structural integrity, particularly in applications where tensile performance is critical.

Flexural Strength

Flexural strength evaluations further emphasized the benefits of fiber reinforcement in improving the bending performance of pervious concrete. As flexural strength is crucial for applications such as pavements and slabs, enhancing it through fiber reinforcement ensures better resistance to cracking and structural deformation.

For NFCA-based mixes, the flexural strength increased from 1.78 MPa to 2.75 MPa with fine aggregate replacement. This improvement suggests that optimizing aggregate gradation enhances the concrete's ability to withstand bending stresses by providing better interlocking and load distribution.

The most substantial improvements were seen in RCA-based mixes reinforced with nylon fibers. At 20% fiber content, the flexural strength reached 4.92 MPa, surpassing all other mix combinations. This superior performance is attributed to enhanced fiber-matrix bonding and crack-bridging capabilities, which significantly improve the material's ability to absorb bending forces without sudden failure. These results highlight the importance of fiber reinforcement in improving the durability and longevity of pervious concrete, making it more suitable for structural applications requiring superior flexural performance.

Impact Resistance

Impact resistance testing assessed the material's ability to absorb energy and resist dynamic loading, which is essential for pavements and load-bearing applications. The results demonstrated that fiber-reinforced mixes exhibited superior resistance to impact forces, further improving the durability of pervious concrete.

For NFCA-based mixes, the first crack resistance was recorded at 20.02 MPa, while ultimate failure resistance reached 55.06 MPa. These values suggest that NFCA provides adequate resistance against impact forces, making it a viable choice for general applications.

However, the highest impact resistance was observed in RCA-based mixes reinforced with nylon fibers. At 20% fiber content, the first crack resistance increased to 25.6 MPa, while ultimate failure resistance reached 70.4 MPa. This significant improvement demonstrates that synthetic fibers enhance the concrete's ability to absorb impact energy, reducing crack propagation and improving overall toughness. The increased impact resistance in fiber-reinforced RCA mixes indicates their potential for use in high-impact applications, such as heavy-duty pavements and industrial flooring.

Hydraulic Properties

Maintaining adequate hydraulic properties, such as permeability and porosity, is essential for ensuring the functionality of pervious concrete in stormwater management and drainage applications. The experimental results revealed a balance between mechanical strength and hydraulic performance, demonstrating the feasibility of fiber-reinforced pervious concrete in practical applications.

The permeability of the tested mixes ranged from 15 mm/s to 19 mm/s, ensuring sufficient infiltration rates for stormwater management. These values indicate that the addition of fibers does not significantly compromise permeability, allowing pervious concrete to maintain its primary function while improving strength and durability.

Similarly, porosity values ranged from 15% to 30%, highlighting a balance between permeability and mechanical strength. While higher porosity levels generally result in improved drainage capacity, they can also lead to reduced strength. However, the incorporation of synthetic fibers helped optimize this balance, ensuring adequate void space for water infiltration while simultaneously enhancing the load-bearing capacity.

These findings suggest that fiber-reinforced pervious concrete offers an optimal combination of mechanical strength and hydraulic performance, making it an excellent choice for sustainable infrastructure applications. By integrating synthetic fibers, the material achieves enhanced durability without sacrificing permeability, ensuring its effectiveness in urban drainage and pavement systems.

The results of this study emphasize the significant role of aggregate type, fiber reinforcement, and mix optimization in enhancing both the mechanical and hydraulic properties of pervious concrete. Synthetic fibers, particularly nylon, significantly improved compressive, tensile, flexural strength, and impact resistance, demonstrating their effectiveness in mitigating cracking and enhancing structural performance. Additionally, the findings confirm that fiber-reinforced pervious concrete maintains adequate permeability and porosity, making it a viable solution for sustainable construction and stormwater management. Future research could explore the long-term durability of fiber-reinforced pervious concrete in real-world conditions to further validate its application in infrastructure projects.

Conclusions

This study comprehensively evaluated the mechanical and hydraulic properties of pervious concrete incorporating natural fine aggregates (NFCA), recycled coarse aggregates (RCA), and synthetic fibers. The results demonstrated that aggregate type, fiber content, and mix optimization significantly influenced compressive strength, tensile strength, flexural strength, impact resistance, and permeability. Based on the findings, the following key conclusions can be drawn:

The results showed that NFCA-based mixes exhibited improved compressive, tensile, and flexural strength with increasing fine aggregate replacement. This can be attributed to better particle packing, which reduced void content and enhanced matrix density. The compressive strength increased from 11.35 MPa to 20.03 MPa at 20% fine aggregate replacement, confirming that optimized gradation improves the structural integrity of pervious concrete. In contrast, RCA-based mixes initially exhibited lower strength due to the presence of adhered mortar, which weakened the interfacial transition zone (ITZ). However, with proper compaction and mix optimization, the compressive strength increased by 138%, reaching 19.23 MPa at 20% replacement. These findings indicate that RCA can be successfully utilized in pervious concrete, provided that appropriate mix design strategies are adopted to counteract the negative effects of adhered mortar.

The inclusion of synthetic fibers had a significant impact on strength enhancement and crack mitigation. Among the fiber types tested, nylon fibers exhibited superior performance, achieving the highest values for compressive strength (23.97 MPa), split tensile strength (2.73 MPa), and flexural strength (4.92 MPa). The improved performance is attributed to nylon's higher tensile strength, stress distribution capacity, and crack-bridging properties. Moreover, impact resistance improved significantly with fiber addition, with RCA mixes containing 20% nylon fibers reaching 70.4 MPa in ultimate failure resistance. This confirms that fibers enhance the concrete's ability to absorb impact energy and reduce crack propagation. Polyethylene and polypropylene fibers also contributed to strength improvements, though their impact was slightly lower compared to nylon. The results highlight the importance of fiber reinforcement in enhancing toughness and durability, making pervious concrete more resilient to mechanical stresses. While strength improvement was a key focus, maintaining adequate permeability and porosity is crucial for stormwater management applications. The study found that fiber addition did not significantly compromise permeability, which ranged from 15 mm/s to 19 mm/s across all mixes. This ensures that water infiltration capacity remains within acceptable limits, allowing pervious concrete to fulfill its primary function in urban drainage systems.

Porosity values ranged from 15% to 30%, balancing permeability with mechanical performance. The findings indicate that optimized mix design and fiber reinforcement can improve pervious concrete's durability without sacrificing its drainage capabilities. This makes fiber-reinforced RCA-based pervious concrete a sustainable and functional alternative to conventional concrete, particularly for applications such as permeable pavements, sidewalks, and stormwater retention systems. The study confirms that synthetic fiber-reinforced RCA-based pervious concrete is a viable and sustainable alternative for construction applications that require both load-bearing capacity and permeability. Given that recycled aggregates are environmentally friendly and contribute to waste reduction, their use in pervious concrete can support sustainable construction initiatives while maintaining adequate strength and durability.

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