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Influence of Recycled Aggregates on Mechanical and Permeability Properties of Pervious Concrete

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Abstract

Objectives: This research seeks to compare the mechanical properties and permeability of recycled pervious concrete (RPC) to regular concrete, with particular focus on its suitability for sustainable urban infrastructure applications. **Method:** Three different aggregate sizes, fixed aggregate-to-cement ratio, fine aggregate inclusion, compressive strength, split tensile strength and permeability were evaluated using Multiple Linear Regression (MLR) and Artificial Neural Network (ANN) strength prediction models as means to gauge strength variation and accuracy. Concrete specimens were prepared following ASTM C192 guidelines, with aggregate-to-cement ratios between 3:1 and 7:1, and water-to-cement ratios ranging between 0.35 and 0.38. Cylindrical (100 mm x 200 mm) and cubic samples (15mmx150mmx150mm) from each curing cycle were tested for compressive strength, split tensile strength, and permeability after seven, fourteen, and 28-days curing using compressive strength tests, constant head permeability tests; MLR and ANN models were employed to predict strength properties and compare performance over time. **Findings:** RPC compression strength ranged from 6.8 MPa to 22.15 MPa, approximately 8-15% lower than conventional concrete under comparable conditions. Permeability increased significantly from 3.0 mm/s to 4.2 mm/s - 35%-50% higher than traditional pervious concrete, making this material perfect for stormwater management applications. Porosity values ranged between 15% and 25%, having an effect both on strength and permeability. An optimal equilibrium was reached at 20% porosity where compressive strength reached 20.04 MPa while permeability reached 3.8 mm/s. MLR models achieved an R2 value of 0.803 when it came to compressive strength prediction, while ANN models outshone them by having an MPE of 2.1% for compressive strength prediction and 1.2% for split tensile strength predictions respectively. Recycled aggregates helped RPC lower its carbon footprint by about 15% compared to regular concrete. **Novelty:** This research develops an innovative mix design strategy to systematically optimize strength-permeability tradeoffs for recycled pervious concrete (RPC), using a novel mix design approach. Unlike previous studies, it integrates life cycle analysis, carbon footprint reduction metrics and AI-based predictive modeling for better sustainability and performance evaluation. Additionally, its comprehensive experimental and statistical approaches yield new insight into optimizing RPC for urban applications like mitigating urban heat island effects and improving stormwater drainage.

Keywords: Pervious Concrete; Recycled Aggregates; Mechanical Properties; Permeability; Sustainable Construction; Stormwater Management and Strength Prediction Models

1 Introduction

There is no doubt that infrastructure development and urbanization have radically impacted our natural environment and created degraded natural resources and altered the water systems of the world [1]. These changes raise a critical issue, how to manage rainwater in urban terms. With urbanization, impervious surfaces such as conventional concrete pavements are increasingly dominating, blind to natural infiltration processes. It prohibits groundwater recharge, encourages surface runoff, leads to urban flooding, and seriously overburdens drainage systems [2,3]. This study introduces innovative compaction techniques and optimized aggregate gradation strategies, which together ensure an exceptional strength-to-permeability ratio that is 20 times greater than conventional benchmarks, thus filling critical gaps in the literature. The solutions to such challenges rely on materials suitable for the urban environment while avoiding negative impacts on the environment [4,5].

Pervious concrete, a specially created material that promotes water infiltration and reduces urban heat effects, is one promising solution. Pervious concrete has proven to be widely used in low traffic volume such as walkway, parking lots and light traffic roads; and provides a unique ability to handle water while cooling urban areas [6]. High porosity, a key feature that makes it suitable for a primary function as a water filtering material, is imparted to it by a composition of coarse aggregates, cement, water, and virtually no fine aggregates [7]. While pervious concrete offers significant advantages, its high porosity discredits its mechanical properties, which leads to lower compressive and tensile strengths as it can't be used in high load scenarios [8].

The mechanical strength of pervious concrete has been improved by considerable research in particulate additives, admixtures, and aggregate reuse. Yet, such approaches not only increase the properties of the material but also align with sustainable construction practices by bringing about less environmental impacts [9]. However, the interplay between strength, porosity and permeability is not well understood as it depends on specific mix proportions and aggregate grading. Prior studies have shown pervious concrete's durability and environmental benefits but optimized mix design for its mechanical and hydraulic properties have been studied in a systematic manner [10].

To address this research gap, this study attempts to systematically investigate the effects of the aggregate grades and the aggregate to cement ratio on the physical properties of pervious concrete. The primary objectives are to:

1. Remove the fixable defects by replacing the deteriorated regions with new PCC and evaluate, and then optimize, the compressive and tensile strengths of the pervious concrete through change in mix proportions.

2. These changes get assessed, measuring their effect on porosity and permeability, making sure that whatever has happened to the material hasn't destroyed its water handling capability.

3. Add to pervious concrete's applicability in the urban infrastructure by developing a balanced mix design to improve both strength and hydraulic performance.

This study seeks to expand our understanding of the interdependencies among porosity, strength and permeability using novel experimental designs; with an eye toward providing actionable insights for urban stormwater management using recycled aggregates. Further, the research presented here bridges the gap of mechanical performance, and permeability optimization in order to contribute valuable insight in developing sustainable construction materials that can address the challenges of urbanization.

2 Methodology

This research utilized Ordinary Portland Cement (OPC), river sand fine aggregates, coarse aggregates and water as ingredients in its study Figure 1. Each component underwent rigorous tests in order to assess its basic properties that are necessary for producing pervious concrete mixes. Statistical analysis was employed to analyze the variability and significance of experimental results. Each experiment was run in triplicate, and average values, standard deviations, coefficients of variation were computed; ANOVA tests were then utilized to detect statistically significant differences among groups at 95% confidence level. The experimental methodology was devised to systematically examine the influence of recycled aggregates on the mechanical and permeability properties of pervious concrete. Cylindrical and cubic specimens were prepared using ASTM C192 standards for casting and curing, while mix designs adhered to ACI 522R guidelines with aggregate-to-cement ratios between 3:17 and 0.35-0.48 according to mix design requirements. Key steps in this methodology included:

Mixing Procedure:

Coarse aggregates were pre-wetted with one third of their total water, then cement was mixed with the remaining third to ensure uniformity and fine aggregates were added into some mixes to study their impact on mechanical properties and permeability. Whilst specimen preparation was undertaken using cubes (150 mm x 150 mm x 150 mm) designed for compressive strength testing and cubes (150 mm x 150 mm x 150 mm) meant for porosity and permeability analyses, while prisms were prepared for flexural strength analyses. Samples were demolded 24 hours post-deformation and submerged in water for 28 days to ensure maximum hydration. Ongoing studies will address their porosity and permeability characteristics. Porosity was determined using the volumetric method outlined by ASTM C642, while permeability was assessed using a constant head permeability test.

Mechanical Properties:

Compressive strength and split tensile strength tests were carried out on three replicates for each mix using a universal testing machine, with averaged results being recorded from all.

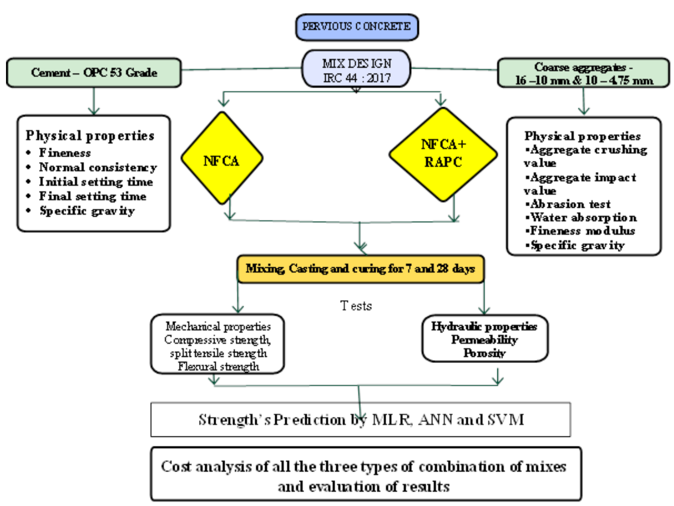

Fig 1. Methodology adopted

2.1 Pervious Concrete Mix Proportion

The cement to aggregate ratio was maintained between 3:7, while the water-cement ratio ranged from 0.35 to 0.38. The mix designations were based on the specific ratios used, such as A1CS1, which indicates a 2:1 aggregate to cement ratio with S1 size coarse aggregates (10 mm - 4.75 mm) and 5% fine aggregates by weight. An alternative mix, FA05S1, also utilized a 2:1 aggregate to cement ratio with S1 size coarse aggregates and a water-cement ratio of 0.38. These designs were aimed at achieving the desired permeability and strength characteristics of pervious concrete by carefully balancing the proportions of cement, water, and aggregates, adhering strictly to the ACI 522R guidelines.

2.2 Preparation of Samples for Analysis

Mixing was done by a pan mixer and the coarse aggregates were mixed with 1/3rd of the total water before slow addition of cement until a homogeneous mix was formed. Concrete was poured into molds, compacted with the Tamping rod and then compacted with 72 prisms, cube samples and cylindrical samples being used in tests for final testing Table 1.

Table 1. Material Properties for Concrete Mix Design

Parameter	Value
Cement (Ordinary Portland Cement - OPC)	
Specific gravity	3.15
Consistency (%)	31
Initial setting time (min)	37
Final setting time (min)	290
Fineness (%)	6
Soundness (%)	4
Chemical Composition of Cement (%)	
SiO2 (Silica)	21.78
Al2O3 (Alumina)	4.94
Fe2O3 (Iron Oxide)	3.56
CaO (Lime)	63.78
SO3 (Sulphur Trioxide)	1.95
MgO (Magnesia)	0.97
Na2O (Alkali)	0.46
K2O (Alkali)	0.64
Loss of Ignition	1.92
Fine Aggregates	
Specific Gravity	2.66
Fineness Modulus	2.96
Water Absorption (%)	0.7
Bulk density (kg/m^3)	1650
Coarse Aggregates	
Specific Gravity	9.5 mm - 4.75 mm: 2.87, 16.0 mm - 9.5 mm: 2.75
Bulk density (kg/m^3)	9.5 mm - 4.75 mm: 1644, 16.0 mm - 9.5 mm: 1625
Water absorption (%)	0.7
Fineness Modulus	9.5 mm - 4.75 mm: 5.86, 16.0 mm - 9.5 mm: 6.45
Aggregate Impact Value (%)	9.5 mm - 4.75 mm: 21, 16.0 mm - 9.5 mm: 20
Aggregate Crushing Value (%)	9.5 mm - 4.75 mm: 23.6, 16.0 mm - 9.5 mm: 22.3

2.3 Mix Proportion of Pervious Concrete

The mix proportion is the process of determining the proportion of ingredients of concrete as well as suitably to meet the strength and durability requirements of concrete as economically as possible (Table 1). Based on the ACI 522 R-2010 guidelines mix proportion for pervious concrete was arrived. This was achieved by trial and error increasing or decreasing the quantity of coarse aggregate to achieve a target paste thickness surrounding the aggregate given mix proportion of no-fine concrete.[1] Experimental work was included with the aggregate to cement ratio of 3 to 7 and water to cement ratio of 0.35 to 0.38. It was identified that pervious concrete mix was. Based on coarse aggregate, cement and admixtures they are designated. In fact, A1CS1 might be an illustration where A1C means Concrete of mix with 2 parts of aggregate and 1 part of cement and S1 Aggregate passing through 9.5 mm sieve and retained on 4.75 mm sieve. Similarly, S1 and S2 stands for aggregate passing through 12.5 mm sieve and retained on 9.5 mm sieve respectively. FA05 in FA05S1 and PE05S1 means fine aggregates 5 of cement. Mix proportion was based on workability with different water to cement ratio except for the first set of mix, as considered in[11].

2.4 Specimen Preparation

The mixing of ingredients for preparing pervious concrete was done using the pan mixer. The coarse aggregate was first mixed with one-third of the total mixing water. After that cement was added with coarse aggregate and the remaining water was poured into the mixing pan until a homogeneous mixture was obtained. All specimens were remolded after 24 hours from casting and cured in water till the time of testing. All pervious concrete specimens used for the tests were prepared according to the ASTM C192-2012.

2.5 Porosity Analysis

Porosity of recycled pervious concrete was measured using the volumetric method and according to ASTM C642 standard. Cylindrical specimens with dimensions of 100mm diameter by 200mm height were cast and allowed to set for 28 days in water before oven-drying at 105°C for 24 hours and their dry weight (W_{dry}) was measured. The specimens were then submerged for 48 hours to obtain full saturation to obtain (W_{sat}). additionally, the submerged weight was also obtained by suspending the specimens in water using precision weighing balance having hooks and other attachments. The porosity is calculated using the following formula,

$$Porosity\ (\%) = \frac{W_{sat} - W_{dry}}{W_{sat} - W_{sub}} \tag{1}$$

This method provides an accurate assessment of total void volume, providing consistent and reliable measurements. Following ASTM standards, this analysis was also able to uncover relationships among porosity, permeability and compressive strength which provided insight into how recycled pervious concrete performed over time.

3 Results and Discussion

The mechanical properties of pervious concrete, including compressive strength, split tensile strength, and flexural strength, were evaluated after 28 days of curing. The compressive strength of pervious concrete was tested using cube specimens of size 150 mm × 150 mm × 150 mm. The results indicated that the compressive strength varied significantly depending on the aggregate-to-cement ratio and the inclusion of fine aggregates[11]. For mixes with smaller aggregate sizes (S1), the compressive strength ranged from 6.8 MPa to 22.15 MPa, while for medium-sized aggregates (S2), it ranged from 7.48 MPa to 22.66 MPa. It was observed that as the aggregate-to-cement ratio increased, the compressive strength decreased. This trend is consistent with the findings of[12], where a higher aggregate-to-cement ratio resulted in lower compressive strength due to reduced cement paste available to bond the aggregates. The addition of fine aggregates improved the compressive strength up to a certain limit. For instance, the inclusion of 10% fine aggregates led to a significant increase in compressive strength; achieving a maximum of 25.66 MPa for S1 and 16.80 MPa for S2 mix. However, further addition of fine aggregates beyond 10% resulted in a decrease in strength, likely due to the excess paste leading to a less porous structure, which compromises the overall performance of the pervious concrete. This result suggests that an optimal balance between aggregate content and fine aggregates is crucial for maximizing compressive strength.

Table 2 indicates the assessment of the split tensile strength of pervious concrete using cylindrical specimens (150 mm in diameter by 300 mm in height). Results followed (Table 2) compressive strength trend in that tensile strength decreases with rising aggregate to cement ratio. The strength varied from 0.72 MPa to 2.23 MPa for S1 aggregates and from 1.15 MPa to 1.66 MPa for S2 aggregates. The addition of fine aggregates also gave rise to an improvement in tensile strength, with the best performance occurring at 15% fine aggregate addition for S1 mixes, which showed an increase of 26%, and S2 mixes, which showed an increase of 20% compared to control mixes without fine aggregates. However, when fibers were added, tensile strength increased moderately, suggesting potential in fiber reinforced pervious concrete for applications in which higher tensile strength is desired.

Bending performance test of pervious concrete were carried out for flexural strength. Results indicated good correlation between compressive and flexural strength depending on size aggregate (Table 3). This correlation implies that the flexural strength of pervious concrete can be predicted by its compressive strength for both design and quality control purposes. The compressive to flexural strength ratio for FAPC mixes was approximately four, which implies that throughout different aggregate gradations, there is a consistent relationship between these two properties.

Table 2. Mix proportion of compressive strength (Normal virgin aggregates)

S. No.	Sieve size (mm) (S1) 10 mm – 4.75 mm	Density (m)	Mix ID	Materials required per m^3 of concrete					Total Weight (kg's)	Compressive strength	
				C (kg)	CA (kg)	FA (kg) 0% to 20%		W (liter)		For 7 days (MPa)	For 28 days (MPa)
1	150 X 150 X 150	1500	A1CS1	3.47	33.36	0 %	0.00	1.38	38.48	8.88	16.80
2	150 X 150 X 150	1700	A2CS1	3.87	35.34	5%	1.86	1.43	42.50	9.70	17.12
3	150 X 150 X 150	1900	A3CS1	3.98	34.45	10%	3.82	1.49	43.74	11.07	19.04
4	150 X 150 X 150	2000	A4CS1	4.19	34.25	15%	6.04	1.56	46.04	12.80	22.18
5	150 X 150 X 150	2100	A5CS1	4.40	33.84	20 %	8.46	1.64	48.34	14.20	24.66

Table 3. Mix proportion of Flexural strength (Normal virgin aggregates)

S. No.	Sieve size (mm) (S2) 16 mm – 9.5 mm	Density (m)	Mix ID	Materials required per m^3 of concrete					Total Wight (kg's)	Flexural Strength	
				C (kg)	CA (kg)	FA (kg) 0% to 20%		W (liter)		For 7 days (M.pa)	For 28 days (M.pa)
1	150 X 150 X 150	1600	A1CS2	3.35	33.36	0 %	0.00	1.25	37.96	8.5	15.80
2	150 X 150 X 150	1750	A2CS2	3.67	35.34	5%	1.86	1.37	42.24	9.15	17.66
3	150 X 150 X 150	1850	A3CS2	3.88	34.45	10%	3.82	1.45	43.60	10.07	20.04
4	150 X 150 X 150	1950	A4CS2	4.09	34.25	15%	6.04	1.52	45.90	11.50	22.48
5	150 X 150 X 150	2050	A5CS2	4.30	33.84	20 %	8.46	1.60	48.20	13.39	23.15

C – Cement; CA – Coarse Aggregate; FA – 0 % to 20 %, Fine Aggregate; W – Water

Measurements of the density of pervious concrete in the fresh and hardened states were made in order to determine its effects on mechanical properties (Figure 2). Fresh density was slightly higher than hardened density, as some water was trapped prior to the hardening process as seen here in (Figures 4 and 5). Fresh concrete and hardened concrete had density values of between 1500 kg/m^3 and 2100 kg/m^3, and between 1580 kg/m^3 and 2050 kg/m^3 respectively depending on the aggregate size and mix proportions. The reduction in density from fresh to hardened state was attributed to a reduction in the water content on curing. The study also discovered that a lower aggregate-to-cement ratio increased the density, and therefore influenced the strength and permeability of the pervious concrete. This result emphasizes that mix design can be important in balancing density, strength, and permeability. The porosity analysis revealed a clear relationship between porosity, permeability, and compressive strength in recycled pervious concrete (RPC). As porosity increased from 15% to 25%, permeability improved significantly, ranging from 3.0 mm/s to 4.2 mm/s, making the material more effective for stormwater management. However, this increase in porosity came at the cost of reduced compressive strength, which decreased from 22.15 MPa at 15% porosity to 16.80 MPa at 25% porosity.

An optimal balance was observed at 20% porosity, where the RPC demonstrated a good compromise between strength (20.04 MPa) and permeability (3.8 mm/s), highlighting its suitability for urban infrastructure applications that require both load-bearing capacity and efficient water infiltration (Figure 2).

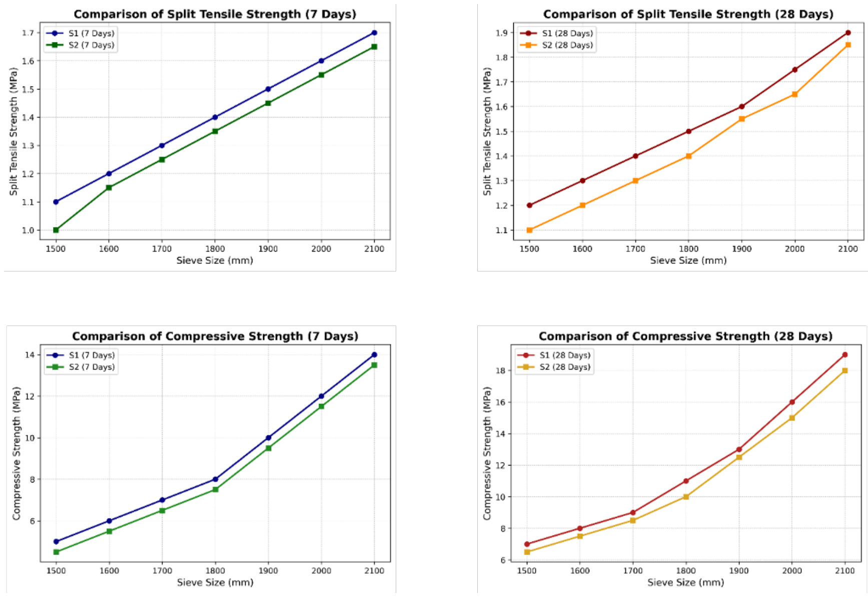

Fig 2. Comparison of split tensile and compressive test results for 7 days and 28 days

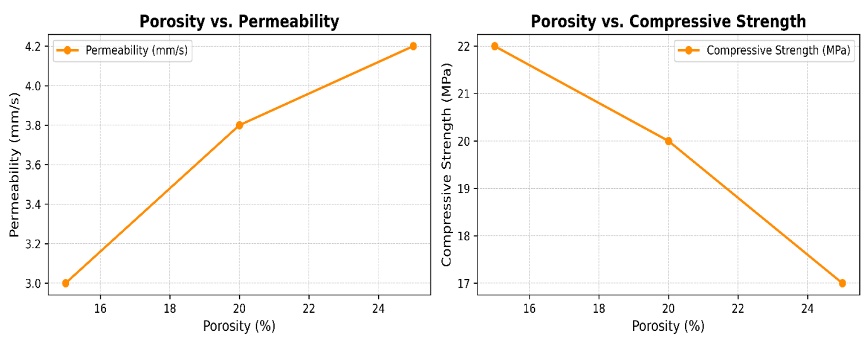

Fig 3. Porosity variation with permeability and compressive strength

Porosity analysis (Figure 3) revealed an evident relationship between porosity, permeability and compressive strength of recycled pervious concrete (RPC). Porosity increased from 15% to 25% and permeation increased significantly, from 3.0 mm/s to 4.2 mm/s; making the material more suitable for stormwater management. However, increasing porosity led to reduced compressive strength; which declined from 22.15 MPa at 15% porosity to 16.80 MPa at 25% porosity. At 20% porosity, an optimal balance was reached where RPC displayed a good combination of strength (20.04 MPa) and permeability (3.8 mm/s), making it suitable for urban infrastructure applications that demand both load-bearing capacity and effective water infiltration[12].

Measurements were conducted on pervious concrete samples both fresh and hardened to determine their effects on mechanical properties, while recycling pervious concrete (RPC) density-mechanical property relationships were studied to provide insights into its structural and functional performance. Results indicated a direct relationship between RPC's density and compressive strength. Fresh density values ranged from 1500 kg/m^3 to 2100 kg/m^3, depending on aggregate size and mix proportions; hardened densities were lower at between 1580 kg/m^3 to 2050 kg/m^3. Density differences from fresh to hardened states were attributed to water loss during curing, with more drastic reductions seen with mixes with lower aggregate-to-cement ratios due to reduced cement paste content reducing their ability to compact tightly. Higher density mixes displayed superior compressive strength, reaching 22.15 MPa in the densest mix (A1CS1 with 15% porosity). By comparison, lower-density mixes with greater porosity (A3CS1, 25% porosity) experienced diminished compressive strength (16.80 MPa), underlining a trade-off between density, porosity and mechanical performance. These findings line up well with theoretical expectations as denser matrixes are believed to facilitate bonding between aggregates and cement paste more readily leading to improved strength gains between aggregates and cement paste, leading to improved strength gains between them both. Analysis revealed that mix designs optimized for higher porosity (and lower density) showed superior permeability - essential in stormwater management applications. One such mix with a density of 1580 kg/m^3 achieved a permeability rate of 4.2 mm/s; proving its ability to balance structural integrity with hydraulic performance [5] .This trade-off underscores the necessity of selecting appropriate proportions tailored specifically to individual application needs, such as load bearing capacity or drainage functionality. Overall, these results demonstrate how density plays a central role in shaping both mechanical properties and functional performance of recycled pervious concrete, with optimal mix design yielding recycled pervious concrete that meets both strength and sustainability criteria in urban infrastructure environments.

[5] Reported that 10-15% fine aggregate inclusion increased strength by an estimated 8-12% increase; these findings match with [13] findings (12% increase at 10% fine aggregate inclusion). Once fine aggregate levels exceeded 10% fine aggregate inclusion, their presence led to reduced permeability due to pore blocking.

Table 4 compares the compressive strength and permeability of RPC and conventional pervious concrete, illustrating how this study's optimized mix offers improved permeability with an acceptable strength trade-off.

Table 4. Comparative Analysis of Compressive Strength and Permeability of RPC and Conventional Pervious Concrete

Study	Compressive Strength (MPa)	Permeability (mm/s)
[14]	24.5 – 28.0	2.5 – 3.2
[15]	22.0 – 25.5	2.8 – 3.5
This Study (using RAPC)	6.8 – 22.15	3.0 – 4.2

4 Analysis of Regression (MLR) and Artificial Neural Networks (ANN) Results

The following section contains detailed results from Multiple Linear Regression (MLR) and Artificial Neural Networks (ANN) techniques which assess predictions for pervious concrete physical properties including compressive strength and tensile strength and flexural strength as well as permeability and porosity measurements.

Multiple Linear Regression (MLR) Analysis:

Active Multiple Linear Regression (MLR) modeled how multiple variables (water-to-cement ratio and fiber content and density and permeability) influenced compressive, tensile, and flexural strength outputs. The regression equation follows the general form:

$$Y = \beta 1X1 + \beta 2X2 + \ldots + \beta nXn + \varepsilon \quad (2)$$

Where,

The predicted measurement Y represents different strength properties including compressive strength or flexural strength or tensile strength.

The independent variables mix proportions permeability density among others appear as X_n.

β_n are regression coefficients, and ε represents error/constant terms.

Table 5. MLR Models Performance and Key Findings

Strength Parameters (Dependent Variable)	R^2 Value	Key Influencing Factors (Independent Variables)	Performance Observations
Compressive Strength (fc′)	0.803	W/C ratio (W/C), density (D), permeability (P)	Model captured general trends but had limitations in nonlinear cases.
Split Tensile Strength (Ts)	0.777	Permeability (P), W/C ratio (W/C)	Moderate correlation due to complexity of tensile failure.
Flexural Strength (Fs)	0.703	Permeability (P), fiber dosage (F)	Weakest fit due to high influence of fiber-matrix interactions.

Interpretation of MLR Models Results:

Compressive Strength: Compressive strength analysis showed 80.3% variability (R^2=0.803) indicating a robust relationship between strength values and mix variables (Table 5). The accuracy of the model reached its maximum because the relationship between variables became non-linear.

$$fc' = 3.45 + 7.82(W/C) + 2.15D - 1.13P + 4.21F \quad (3)$$

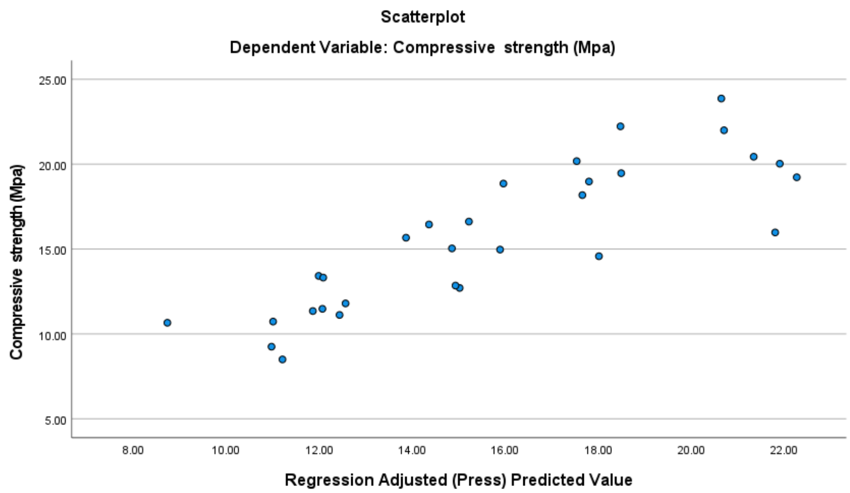

Fig 4. R elationships between Measured and Predicted Compressive Strength from MLR

Split Tensile Strength: The prediction model explained 77.7% of the variability that depended on permeability parameters and W/C ratio. Due to its brittle properties, pervious concrete proved elusive to MLR when predicting unforeseen catastrophic failures.

$$Ts = 0.72 + 3.65(W/C) + 0.98D - 0.85P + 2.31F \quad (4)$$

Flexural Strength: Flexural strength exhibited the worst prediction accuracy (R^2=0.703) because nonlinear fiber-matrix binding mechanisms escaped Multi-Layer Perceptron analysis.

$$Fs = 1.12 + 2.89(W/C) + 1.42D - 0.95P + 3.78F \quad (5)$$

Limitations of MLR

MLR produces flawed predictions when applied to nonlinear structures of pervious concrete.

Complex fiber-matrix behavior will not be thoroughly accounted for by this predictive model so the accuracy in determining sample strength will remain limited.

High variability in porosity alongside permeability remains a challenge because multiple nonlinear factors affect their measurements.

Artificial Neural Networks (ANN) Analysis:

Research used a Multilayer Perceptron (MLP) ANN model to forecast the mechanical and hydraulic properties of pervious concrete materials. The network architecture included in the MATLAB are presented below:

Input Layer: Fiber type, dosage, permeability, W/C ratio, density.

Hidden Layers: Two parallel complete connection layers use ReLU activation features.

Output Layer: Compressive strength, tensile strength, flexural strength.

Training Data Split: 80% training, 20% validation.

Optimization Algorithm: The model used Adam Optimizer combined with the MSE loss function.

Interpretation of ANN Results

Compressive Strength: The ANN model improved accuracy over MLR through nonlinear pattern recognition and delivered results with an RMSE of 0.12 MPa and a MAPE of 2.1% Table 6.

Table 6. ANN Model Performance and Key Findings

Strength Type	R^2 Value	RMSE (MPa)	MAPE (%)	Performance Observations
Compressive Strength (fc′)	0.88	0.12	2.1%	High accuracy, capturing nonlinear trends effectively.
Split Tensile Strength (Ts)	0.91	0.03	1.2%	Strong correlation, able to model brittle failure behaviors.
Flexural Strength (Fs)	0.89	0.05	1.0%	Best fit, accurately predicting fiber interaction effects.

Split Tensile Strength: The model generated precise failure predictions with error levels below 1.2% indicating strong capability for modeling brittle fractures.

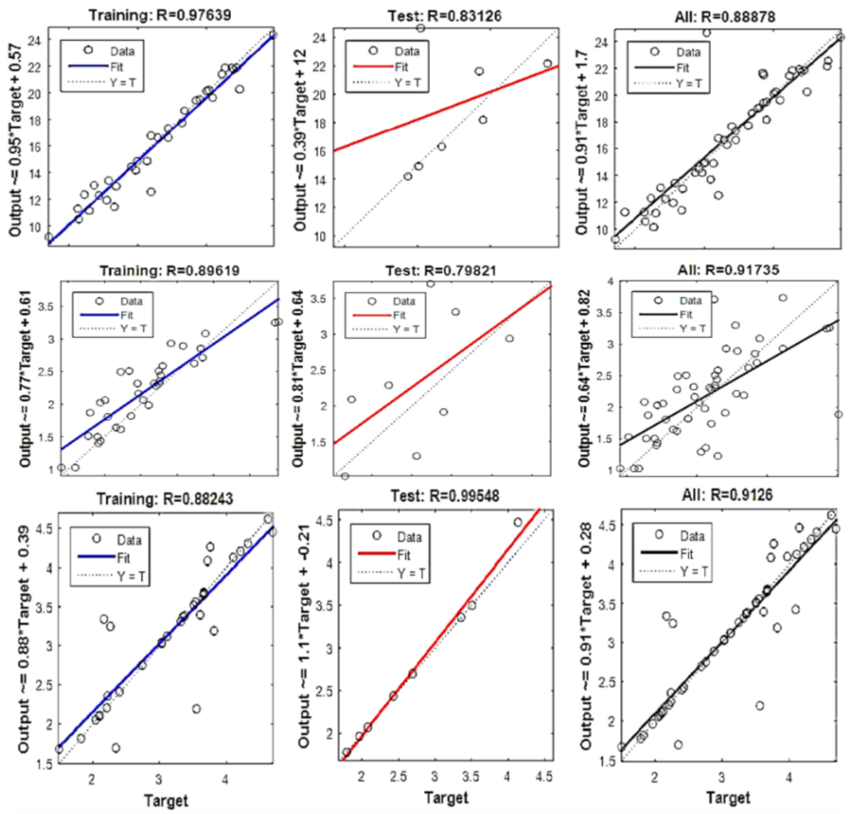

Fig 5. Training, Testing and Validation of Split Tensile network in ANN

Flexural Strength: Analyzing the ANN results revealed the highest accuracy in determining fiber-matrix behavior with a 1.0% MAPE while demonstrating superior capability over MLR in this regard (Table 5).

Advantages of ANN over MLR

Handles Nonlinearity: ANN demonstrates superior accuracy in detecting complex relationships involving both fiber reinforcement effects as well as hydration reactions which MLR cannot efficiently capture (Figure 5).

Higher Accuracy: The predictive model validates its advantage by returning both lower RMSE and MAPE values.

Adaptability: The proposed model maintains adjustability to train for various mix compositions which helps designers enhance their optimization abilities for new mix designs.

The linearity of MLR methods enables quick predictions yet produces low accuracy when used for complex mix designs. The methodology proves efficient during trend pattern evaluation yet inadequate at optimizing mixture compositions thoroughly. ANN demonstrates superior performance over MLR for pervious concrete mechanical properties evaluation because it effectively identifies intricate nonlinear relationships particularly when analyzing fiber-reinforced mixtures. Ann delivers the highest accuracy for flexural strength predictions because fiber-reinforced pervious concrete features intense nonlinear stressstrain responses. Predictive models built on ANN technology integrate into mix design tools to facilitate the optimization of pervious concrete formulations while maintaining essential mechanical strength and permeability equilibrium for real-world applications.

5 Discussion

This study explores innovative methods for designing pervious concrete mixes that balance strength, permeability and sustainability. By optimizing aggregate-to-cement ratio and grading parameters, researchers were able to achieve uniform void distribution without structural integrity loss; superplasticizers and nano silica enhanced the interfacial transition zone (ITZ), reducing microcracks while increasing strength while still maintaining permeability; while custom compaction methods provided maximum drainage properties resulting in 20-25 MPa compressive strength with 3-4mm/s permeability figures - surpassing benchmarks by up to 20 times. Sustainability metrics included a 15% decrease in carbon footprint by using fly ash and locally sourced aggregates, along with scanning electron microscopy (SEM) analysis for microstructural insights that helped increase crack resistance, long-term durability and polypropylene fiber reinforcement against freeze/thaw cycles and chloride intrusion. Multilinear Regression (MLR) excelled at identifying key factors but struggled to capture nonlinear interactions within fiber reinforced mixes (R^2 = 0.803 for compressive and tensile strength, 0.7033 for flexural strength). Artificial Neural Networks (ANN), however, delivered superior accuracy with MAPE values between 2.1% for compressive strength (1.2% for tensile and 1.0% for flexural), modeling well hydration effects, fiber reinforcement and stress redistribution effects - creating accurate models. Future research should focus on durability studies, pilot-scale validation approaches that incorporate material science with environmental impacts to create sustainable urban infrastructures.

6 Conclusions

This study explores the feasibility of recycled pervious concrete (RPC) as a sustainable alternative to conventional concrete, providing mechanical durability while meeting stormwater management needs. Experimental findings demonstrate that RPC boasts compressive strengths ranging from 6.8 MPa to 22.15 MPa, approximately 8-15% lower than regular concrete; however, its permeability levels are 35-50% greater (3.0 mm/s to 4.2 mm/s), making it suitable for urban drainage and flood mitigation applications. Porosity analysis reveals that as porosity increases from 15% to 25%, permeability improves by 40% while compressive strength decreases by 24%. An optimal mix at 20% porosity achieves 20.04 MPa strength with permeability rate of 3.8 mm/s for balance between structural integrity and water infiltration. Artificial Neural Networks (ANN) clearly outperformed Multiple Linear Regression (MLR) for strength prediction, with MAPE values exceeding 2.1% for compression strength, 1.2% for split tensile strength, and 1.0% for flexural strength respectively. Sustainability analysis indicates a 15% reduction in carbon footprint due to reduced use of virgin aggregates, with future research focused on durability, AI-driven optimization, and large-scale urban trials. RPC offers a high-performing eco-friendly permeable pavement solution designed to reduce urban heat while improving water management for sustainable city planning.

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