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TECHNICAL PAPER

Performance evaluation and exploratory regression analysis of pervious geopolymer concrete incorporating engineered synthetic aggregates

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Abstract

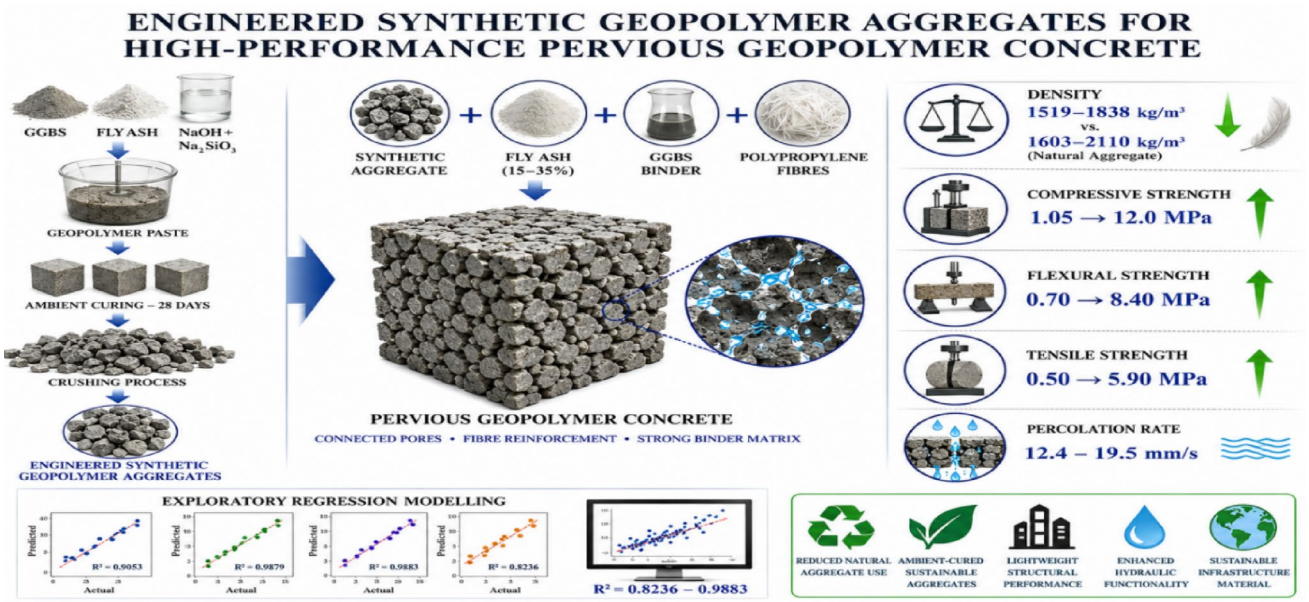
The increasing demand for sustainable construction materials has accelerated the development of alternative aggregate systems for pervious concrete. This study investigates the performance of fly ash-based pervious geopolymer concrete incorporating engineered synthetic aggregates manufactured from alkali-activated ground granulated blast furnace slag (GGBS). Class F fly ash with 5% silica fume was used as the geopolymer binder, activated by a sodium hydroxide to sodium silicate solution. Five mixtures were prepared by simultaneously varying the fly ash (15–35%) and coarse aggregate (80–60%) contents on a mass basis. The density, compressive strength, flexural strength, splitting tensile strength, and percolation rate of mixtures containing engineered synthetic aggregates were experimentally compared with corresponding natural aggregate mixtures. The synthetic aggregate mixtures exhibited lower dry densities (1519–1838 kg/m^3) than the natural aggregate mixtures (1603–2110 kg/m^3). Compressive strength increased from 1.05 to 12.00 MPa for synthetic aggregate mixtures and from 2.18 to 10.50 MPa for natural aggregate mixtures. At higher fly ash contents, synthetic aggregate mixtures achieved superior mechanical performance while maintaining higher percolation rates. Exploratory regression analysis yielded strong empirical correlations (R^2 = 0.8236–0.9883), describing trends within the investigated dataset. The findings demonstrate the technical feasibility of using GGBS-based engineered synthetic aggregates as a sustainable alternative to natural coarse aggregates in pervious geopolymer concrete under laboratory conditions.

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Graphical abstract



Keywords Pervious geopolymer concrete · Engineered synthetic aggregate · Fly ash · Mechanical properties · Percolation rate · Exploratory regression analysis

Introduction

Rapid urbanization and extensive surface paving have significantly altered natural hydrological cycles, resulting in increased stormwater runoff, urban flooding, groundwater depletion, and deterioration of water quality [1–3]. Pervious concrete has emerged as an effective sustainable construction material capable of mitigating these challenges by facilitating rainwater infiltration through interconnected pore networks. In addition to improving stormwater management, pervious concrete contributes to groundwater recharge, reduction of surface runoff, and enhancement of urban environmental sustainability [4, 5]. However, the relatively low mechanical strength of conventional pervious concrete remains a major limitation restricting its wider structural application.

Simultaneously, the construction industry faces growing pressure to reduce its environmental footprint by minimizing the consumption of natural resources and lowering greenhouse gas emissions associated with conventional cement production [6]. Geopolymer technology has attracted considerable attention as a sustainable alternative to ordinary Portland cement due to its ability to utilize industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS) as primary binder materials. Geopolymer binders not only reduce carbon emissions but also offer favourable engineering properties, including improved chemical resistance, thermal stability, and long-term durability [7, 8].

Fly ash is one of the most abundantly available industrial by-products generated from thermal power plants. Although significant quantities of fly ash are utilized in cementitious materials, large volumes continue to be disposed of in landfills, creating environmental and economic concerns. The valorization of fly ash through geopolymerization provides an attractive pathway for transforming industrial waste into high-value construction materials [7, 8]. Beyond its use as a binder precursor, fly ash can also be employed for the development of engineered synthetic aggregates, thereby reducing dependence on natural aggregates and promoting circular resource utilization [9, 10].

Aggregates constitute a major volume fraction of concrete and strongly influence its mechanical and hydraulic performance. Excessive extraction of natural aggregates has led to resource depletion and ecological degradation in many regions worldwide. Consequently, the development of alternative aggregate systems derived from industrial by-products has become an important area of research. Previous studies have investigated recycled aggregates, lightweight aggregates, artificial aggregates, and industrial waste-derived aggregates for concrete applications. While these investigations have demonstrated varying degrees of success, limited research has focused on geopolymer-derived

engineered synthetic aggregates incorporated within fully geopolymerized pervious concrete systems [11–13].

Recent studies on geopolymer pervious concrete have primarily concentrated on the influence of binder composition, aggregate gradation, porosity, and permeability characteristics. Similarly, investigations involving artificial or synthetic aggregates have often focused on either mechanical performance or hydraulic behavior. However, comprehensive evaluations incorporating engineered synthetic aggregates, direct comparison with natural aggregate systems, and simultaneous assessment of density, compressive strength, flexural strength, splitting tensile strength, and percolation behavior remain relatively limited. Furthermore, studies examining performance relationships among these engineering properties and developing predictive performance trends are comparatively scarce [11–13].

Although considerable research has been conducted on pervious geopolymer concrete and artificial aggregate technologies, the focus of previous studies has largely remained on either geopolymer binder optimization or alternative aggregate utilization independently. Comparatively fewer investigations have explored the combined application of engineered synthetic aggregates within pervious geopolymer concrete while simultaneously evaluating the mechanical, hydraulic, and empirical performance characteristics. To provide a clearer perspective on the current state of research, Table 1 summarizes representative studies published on geopolymer pervious concrete and artificial aggregate systems, highlighting their principal findings, limitations, and the remaining research opportunities addressed in the present work.

The present study addresses these research gaps through the development and evaluation of geopolymer pervious concrete incorporating geopolymer-based engineered synthetic aggregates produced from fly ash and alkaline activators. Unlike conventional aggregate systems, the engineered synthetic aggregates were manufactured through geopolymerization and crushing of geopolymer solid blocks to produce aggregate particles suitable for concrete applications. The performance of synthetic aggregate mixtures was systematically compared with corresponding natural aggregate mixtures under identical geopolymer binder conditions.

The objectives of this study were to: (i) develop engineered synthetic aggregates from GGBS-based geopolymer materials; (ii) investigate the influence of aggregate type and fly ash content on density, compressive strength, flexural strength, splitting tensile strength, and percolation rate of geopolymer pervious concrete; (iii) examine relationships among key engineering properties; and (iv) develop exploratory regression models to assess performance trends within the investigated experimental range.

Table 1 Comparison of representative studies on geopolymer pervious concrete and engineered/artificial aggregate systems

Reference	Binder system	Aggregate type	Research focus	Key findings	Limitations	Research gap
[14]	High-calcium fly ash + $NaOH/Na_2SiO_3$	Natural coarse aggregate	Mechanical behaviour of pervious geopolymer concrete (PGC)	Compressive and flexural strength increased with density; void–strength relationships established	Only natural aggregate used; no artificial/synthetic aggregate variant	No exploration of engineered aggregate substitution in PGC
[15]	Coal (fly + bottom) ash geopolymer binder	Coal-ash-derived coarse aggregate	Coupled use of ash as both binder and aggregate	Comparable strength to OPC pervious concrete at similar porosity	Aggregate not engineered/pelletized; inconsistent particle shape	Lacks systematic aggregate engineering methodology
[16]	High-calcium fly ash geopolymer	Recycled concrete/clay-brick aggregate	Recycled aggregate substitution in PGC	RCA and RBA increased permeability; strength reduced at 100% replacement	Recycled aggregate quality variable and source-dependent	No engineered/manufactured aggregate alternative studied
[17]	Fly ash geopolymer	Geopolymer-coated palm-oil biomass aggregate	Permeability–strength relationship with coated bio-aggregate	Geopolymer coating improved ACV, AIV and compressive strength versus uncoated aggregate	Biomass aggregate strength inherently limited; regional material dependency	Coating improves performance but aggregate core remains weak
[18]	GGBS:FA (1:0, 1:1) geopolymer	Recycled concrete aggregate (0–100%)	Mechanical, permeability and durability performance of PGC	RCA and higher FA fraction reduced density, strength and abrasion resistance; permeability increased	No regression/predictive modelling of the generated dataset	Empirical results not translated into predictive relationships
[19]	GGBS + fly ash, alkali-activated	Cold-bonded pelletized artificial lightweight aggregate	Orthogonal optimization of GGBS ratio, alkali equivalent and modulus on aggregate/concrete performance	Aggregate strength >10 MPa, bulk density <1050 kg/m^3; good aggregate–matrix bonding	Aggregate produced and tested only in dense (non-pervious) concrete	Engineered aggregate not evaluated in pervious/hydraulic applications

The findings contribute to the growing body of knowledge on sustainable geopolymer construction materials and provide preliminary insights into the feasibility of utilizing geopolymer-derived engineered synthetic aggregates in pervious concrete systems. Nevertheless, application-specific validation, detailed microstructural characterization, long-term durability assessment, and independent model validation remain important areas for future research.

Experimental programme

The experimental program was structured into two interlinked phases, as illustrated in Fig. 1. The first phase focuses on the production of geopolymer aggregates via the alkali activation of GGBS, developing a regulated method for obtaining chemically bonded, high-strength engineered synthetic aggregates (SA). The second phase comprises the development and detailed analysis of permeable geopolymer concrete, which integrates both the synthetic aggregates and the conventional natural coarse aggregates [20].

This two-phase framework was intentionally strategized to produce a structure that was capable of satisfying both performance requirements of a high structural integrity and an effective permeability. The mixtures and curing methods were done under normal laboratory conditions to facilitate the practical, low-energy curing environments and to increase the possibility of real-world implementation [21].

Further, the experimental programme was designed to investigate the influence of overall mixture composition rather than the isolated effect of a single constituent. During mixture development, the fly ash content was increased

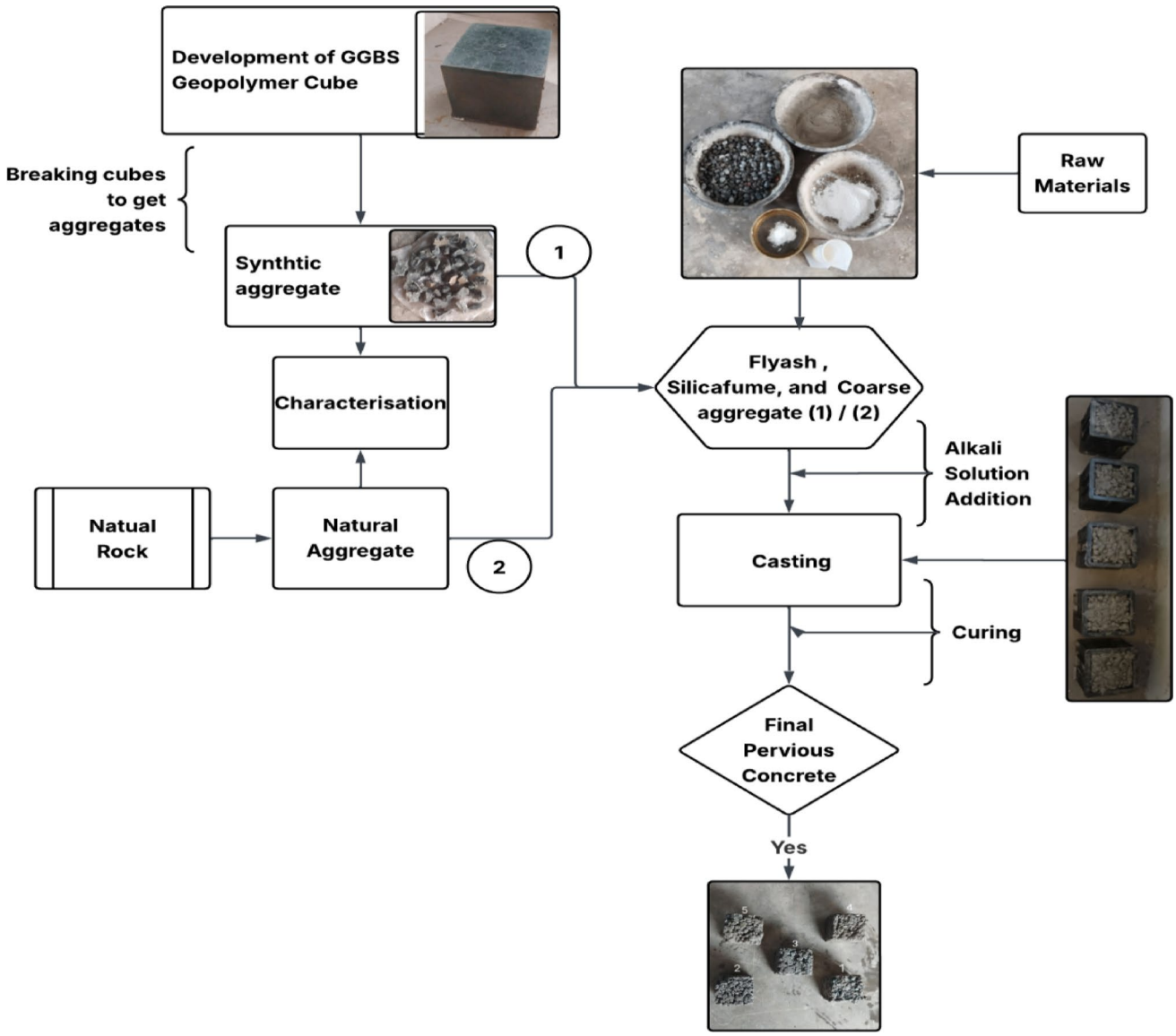


Fig. 1 Experimental programme for the development of pervious geopolymer concrete

Table 2 Chemical properties of raw materials

Materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O & K_2O	Loss on ignition (LOI)
GGBS	28.6	20.8	0.9	41.3	7	0.3	0.6	< 1
Fly ash	58	22	10	4	2	1.5	1	< 2.5

Table 3 Mix proportion for geopolymer solid cube

GGBS	Alkali activator*
71%	29%

*NaOH (10 M): Na_2SiO_3 =1:2.5

while the coarse aggregate proportion was reduced correspondingly to maintain the target mixture proportions. Consequently, the observed changes in mechanical and hydraulic performance should be interpreted as the combined response to the modified mixture composition rather than as the exclusive effect of fly ash content.

Materials

In this study, GGBS was selected as the primary raw material for the development of engineered synthetic aggregate (SA) due to its high calcium and amorphous content, which favoured the rapid geopolymerization process. For the development of pervious concrete mixes, Class F fly ash was used as the main aluminosilicate precursor, and silica fume was added at a constant dosage of 5% of the binder to improve the packing density and microstructural refinement [22–25]. The chemical combination of GGBS and fly ash is expressed in Table 2.

In natural aggregate (NA) mixtures, conventional crushed stone are utilised as the coarse aggregate source, whereas the engineered synthetic aggregates (SA) were produced by crushing hardened geopolymer solid cubes into aggregate-sized particles. The production of SA includes the alkali activation of GGBS using a blended alkaline activator comprising sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The mix proportions used for the production of the geopolymer solid cubes are presented in Table 3.

Initially, GGBS was dry mixed to ensure homogeneity, after which the alkaline activator solution was gradually added and mixed until a uniform geopolymer paste was obtained. The fresh geopolymer mixture was then cast into steel cube moulds with dimensions of 150 mm × 150 mm × 150 mm. The specimens were cured under ambient laboratory conditions for 28 days to simulate practical field-curing conditions while minimizing the additional energy requirements associated with thermal curing. Following curing, the geopolymer cubes were mechanically crushed to produce engineered synthetic aggregates. The crushed material was subsequently sieved to obtain coarse aggregate-sized fractions suitable for the preparation of geopolymer pervious concrete mixtures [26, 27].

Table 4 Physical and mechanical properties of raw materials

Properties	GGBS	Fly Ash (Class F)	Natural coarse aggregate (NA)	Synthetic aggregate (SA)
Specific gravity	2.9	2.25	2.81	2.18
Particle size (μm)	< 75	< 100	*	*
Bulk density (kg/m^3)	1100	980	1745	1080
Water absorption	–	–	0.36	0.23
Aggregate impact value (%)	–	–	11.3	10
Aggregate crushing value (%)	–	–	22.5	19

*Comparative particle size distribution of natural and synthetic aggregate is discussed in the subsequent section

Although manual crushing was adopted in the present laboratory-scale investigation, industrial implementation can utilize automated crushing and grading systems to ensure controlled particle size distribution, shape consistency, and reproducible aggregate quality. Therefore, the term 'engineered synthetic aggregate' refers to the intentional geopolymer-based aggregate production process with controlled chemistry and gradation characteristics.

The aggregates were characterised for their particle size distribution (IS383) [28], specific gravity (IS 2386 Part 3), bulk density (IS 2386 Part 3), and water absorption (IS 2386 Part 3). The mechanical characterisation, together with aggregate crushing value (IS 2386 Part 4) and impact value (IS 2386 Part 4), was also done to check their performance in pervious concrete [29]. The physical and mechanical properties of raw materials are shown in Table 4.

The alkaline activator solution consisted of a 10 molar (10 M) sodium hydroxide (NaOH) solution mixed with a sodium silicate (Na_2SiO_3) solution at a ratio of 1:2.5, which was prepared 24 h before use to stabilize its viscosity and reaction potential, and the sodium silicate solution had a modulus (SiO_2/Na_2O) of 2.5. These chemicals are analytical grade and procured from Sigma Aldrich, India [25, 30–32]. All mixes were integrated with polypropylene (PP) fibres at a rate of 1% of the binder mass to enhance tensile resistance and reduce the occurrence of brittle cracking [33, 34]. Before usage, all the raw materials are stored and conditioned at the ambient laboratory temperature. Silica fume that was used in this study had a specific surface area around 22,000 m^2/kg, and the SiO_2 content was over 93%, which helped it fill micro spaces better and refine the pores inside the geopolymer matrix. Also, PP fibres were 12 mm long,

with a density of 0.89 g/cm^3, were added in order to increase crack resistance and improve post cracking behaviour.

Particle size distribution of synthetic and natural aggregate

The particle size distribution of the SA and natural aggregate NA is displayed in Fig. 2. The grading behaviour of the two aggregate types is clearly shown to be different by the cumulative percentage passing for each sieve size.

The PSD analysis confirms the complete absence of both SA and NA at the 40 mm sieve, indicating that the aggregates' size is appropriate for common pervious concrete uses. Nonetheless, the SA, in the case of the 20 mm sieve, reveals a total passing of 47%, which is considerably lower than the 69% for NA. It can thus be inferred that SA holds a larger quantity of coarse particles in the upper size fraction, possibly due to the irregular breakage pattern that occurs during manual fragmentation of geopolymer cubes.

The same pattern is seen at the intermediate sieve sizes of 12.5 and 10 mm, SA has 78% and 86% passing, respectively, while NA has 85% and 96% for the same levels. The cumulative passing for SA (94%) at the 4.75 mm sieve remains just a little bit lower than that for NA (99%) [35–37]. This minute difference reveals that NA has a larger quantity of small-sized particles, which is typical for naturally weathered aggregates and aids in the formation of denser packing.

This grading difference is of great importance in determining the performance of pervious concrete mixtures. The coarse grading of SA will probably result in a larger void volume and better permeability, better compaction, and mechanical interlock [28, 35–38]. These tendencies agree with the usual trends in pervious concrete where aggregate shape and distribution are the key factors for both hydraulic and mechanical behaviour.

Development of geopolymer pervious concrete and characterisation

A total of ten geopolymer pervious concrete mixes were developed, which included five mixes with SA (S1–S5) system and five mixes with NA (N1–N5) system, as expressed in Table 5, and the methods of development are illustrated in Fig. 3. The fly ash content was continuously altered from 15 to 35%, while a consistent addition of 5% silica fume was maintained for all mixes. The amount of aggregate was modified such that the total mass remained the same, and the liquid-to-binder ratio was maintained at 0.52 to evaluate its influence on the performance of the mixtures on pore structure and mechanical behaviour. The liquid-to-binder ratio of 0.52 was selected based on preliminary trial mixtures, where lower ratios resulted in insufficient workability and incomplete aggregate coating, while higher ratios caused excessive paste flow and pore blockage. The selected ratio provided an optimal balance between mechanical integrity and permeability retention. The application of PP fibres was done at 1% of the binder mass in every mix.

In the development of pervious concrete, the mixing process is crucial, as it is responsible for the uniform and proper dispersion of the fibers, along with the prevention of the flow of the excessive paste into the voids. Aggregates and PP fibers were first mixed together until there was uniformity. Then, the dry precursors (fly ash and silica fume) were added and mixed well. Later, the alkali activator solution was slowly added, and the mixing was continuous until the binder had coated the aggregate particles sufficiently while allowing an open-graded structure to be maintained. The fresh concrete was then poured into the molds for the compressive strength cubes, flexural beams, and tensile test cylinders. The standard dimensions of the specimen for the assessment of mechanical properties of concrete, is shown in Table 6.

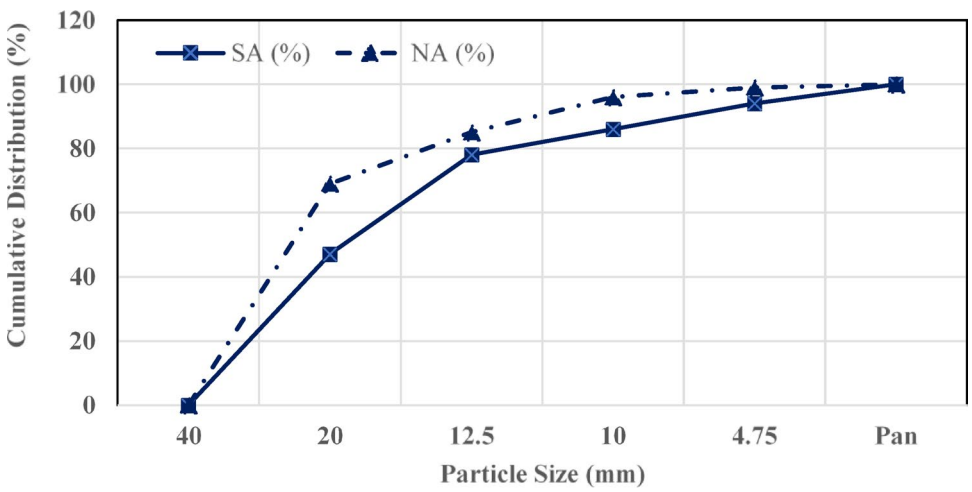


Fig. 2 Particle size distribution of synthetic versus natural aggregate

Table 5 Mix proportion of geopolymer pervious concrete

Mix ID	Mix details	Fly ash (kg/m^3)	Silica fume (kg/m^3)	Synthetic aggregate (kg/m^3)	Natural aggregate (kg/m^3)	PP fibre (kg/m^3)	Alkaline activator/ binder ratio
S1	15FA:80CA**	316.5	105.5	1688	–	21.1	0.52
S2	20FA:75CA**	422	105.5	1582.5	–	21.1	0.52
S3	25FA:70CA**	527.5	105.5	1477	–	21.1	0.52
S4	30FA:65CA**	633	105.5	1371.5	–	21.1	0.52
S5	35FA:60CA**	738.5	105.5	1266	–	21.1	0.52
N1	15FA:80CA**	316.5	105.5	–	1688	21.1	0.52
N2	20FA:75CA**	422	105.5	–	1582.5	21.1	0.52
N3	25FA:70CA**	527.5	105.5	–	1477	21.1	0.52
N4	30FA:65CA**	633	105.5	–	1371.5	21.1	0.52
N5	35FA:60CA**	738.5	105.5	–	1266	21.1	0.52

CA**—Coarse aggregate synthetic/natural aggregate; unless otherwise specified, all mixture proportions and replacement percentages presented in this study are expressed on a mass basis

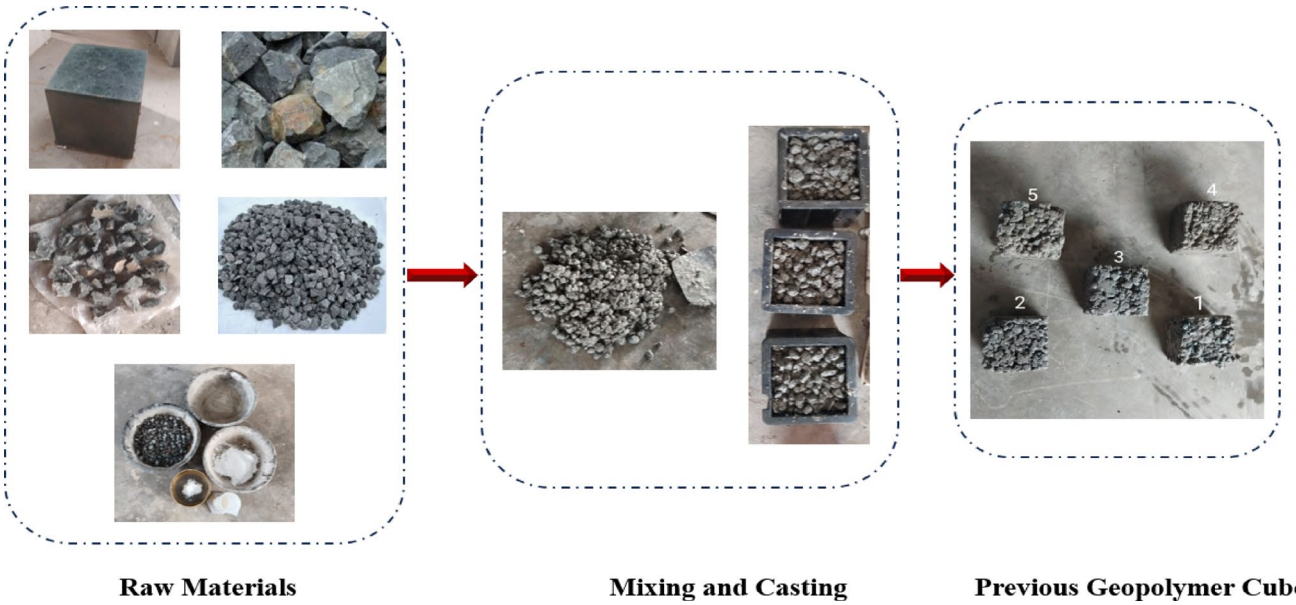


Fig. 3 Methods of development of pervious geopolymer concrete cube

Table 6 Concrete sample dimensioning as per Indian standards

Properties	Compression	Flexure	Splitting tension	Reference
Standard specimen	150×150 × 150 mm^3	100×100 × 500 mm-Prism	Φ150 × 300 mm-Cylinder	[39, 40]

The concrete mixtures were compacted manually rather than by mechanical vibration to preserve the interconnected pore network essential for the permeability characteristics of pervious concrete. Mechanical vibration was intentionally avoided because excessive compaction may reduce pore connectivity and adversely affect hydraulic performance [21, 26, 27, 29]. All specimens were cured under ambient laboratory conditions and tested after 28 days of curing in accordance with the adopted testing procedures [21, 26, 27, 29]. For each mixture, three replicate specimens were cast and tested for every measured property. The reported results represent the average values obtained from the three specimens, while the corresponding standard deviation (SD) and coefficient of variation (COV) values were calculated to assess experimental variability and repeatability.

Experimental tests

The dry density of the hardened concrete specimens was determined in accordance with IS 1199 (Part 2): 2018. Prior to testing, the specimens were dried in an oven maintained at 105 ± 5 °C until a constant mass was achieved, ensuring the complete removal of free moisture. The dry density of each specimen was then calculated as the ratio of the oven-dry mass to the measured volume of the specimen [29, 41].

The compressive strength of the geopolymer pervious concrete specimens was determined in accordance with IS 516 (Part 1/Sect. "Introduction"): 2021 using standard cube specimens measuring 150 mm × 150 mm × 150 mm. The specimens were subjected to a uniformly applied load at a loading rate of 0.6 ± 0.2 MPa/s until failure. The maximum load sustained by each specimen was recorded and used to calculate the compressive strength [39], as expressed in Eq. (1).

$$f_c = \frac{P}{A} \tag{1}$$

where P is the maximum load at failure (N), and A is the loaded area of the specimen (mm^2).

Flexural strength (modulus of rupture) was assessed in accordance with IS 516 (Part 2/Sect. Introduction"): 2021[42–44]. Three-point loading was applied to prismatic specimens of size 100 × 100 × 500 mm, and the calculation of the flexural strength was done based on the load at which the specimen failed and its geometry, and is expressed in Eq. (2).

$$f_r = \frac{PL}{bd^2} \tag{2}$$

where P is the maximum load at failure (N), L is the span between the supports (mm), and b and d are the width and depth of the specimen, respectively.

The split tensile strength was determined in accordance with IS 5816: 1999[45]. The cylindrical samples (150 mm in diameter and 300 mm in height) were laid in a horizontal position, and a load was applied to the vertical diameter until the specimen split, then the strength was calculated, as per Eq. (3).

$$f_{st} = \frac{2P}{\pi DL} \tag{3}$$

where P is the maximum applied load (N), D and L are the diameter and length of the specimen (mm), respectively.

The hydraulic performance of the geopolymer pervious concrete mixtures was evaluated using a laboratory-scale percolation test developed according to the fundamental infiltration principles of ASTM C1701 while recognising that ASTM C1701 is intended for field evaluation of in-place pervious concrete pavements. Cylindrical specimens (100 mm dia and 200 mm height) were positioned vertically, and their lateral surfaces were sealed to ensure one-dimensional water flow through the specimen thickness. Prior to testing, the specimens were preconditioned under saturated surface-dry conditions to minimise the influence of initial moisture absorption. A fixed volume of 500 mL of water was introduced under a constant hydraulic head, and the infiltration time required for the water to pass through the specimen was recorded. The percolation rate was calculated by dividing the effective flow distance by the measured infiltration time and is reported in mm/s. The selected water volume provided complete infiltration through all specimens while maintaining consistent testing conditions for comparative evaluation. The adopted procedure should therefore be regarded as a controlled laboratory comparison of hydraulic performance and should not be interpreted as a direct equivalent of field infiltration measurements obtained using ASTM C1701.

Each mixture was tested using three replicate specimens, and the reported values correspond to the average of the measured results. The adopted procedure enabled a consistent comparison of the hydraulic performance of mixtures containing engineered synthetic aggregates and natural aggregates under identical laboratory conditions. The measured percolation rate serves as an indicator of the water transmission capability of the pervious geopolymer concrete and provides a practical assessment of its potential suitability for permeable pavement and drainage-related applications.

Statistical and exploratory regression modelling procedure

Statistical and exploratory regression analyses were performed to investigate the relationships between the mechanical and hydraulic properties of geopolymer pervious concretes produced using SA and NA. The objective of the analysis was to examine whether performance trends observed in one aggregate system were associated with corresponding trends in the other system and to provide preliminary insights into potential property relationships within the investigated experimental range [46, 47].

A paired dataset was established for each measured property, including density, compressive strength, flexural strength, splitting tensile strength, and percolation rate. For each property, results obtained from NA mixtures were paired with those from SA mixtures incorporating the same binder composition. Ordinary least-squares (OLS) linear regression was adopted as an exploratory analytical tool because preliminary inspection of the data indicated approximately linear relationships between the paired variables [48, 49].

Owing to the limited dataset size, the regression models should be considered exploratory and are intended to describe observed trends rather than establish universally applicable predictive relationships. For each property, the regression coefficients were calculated using the standard

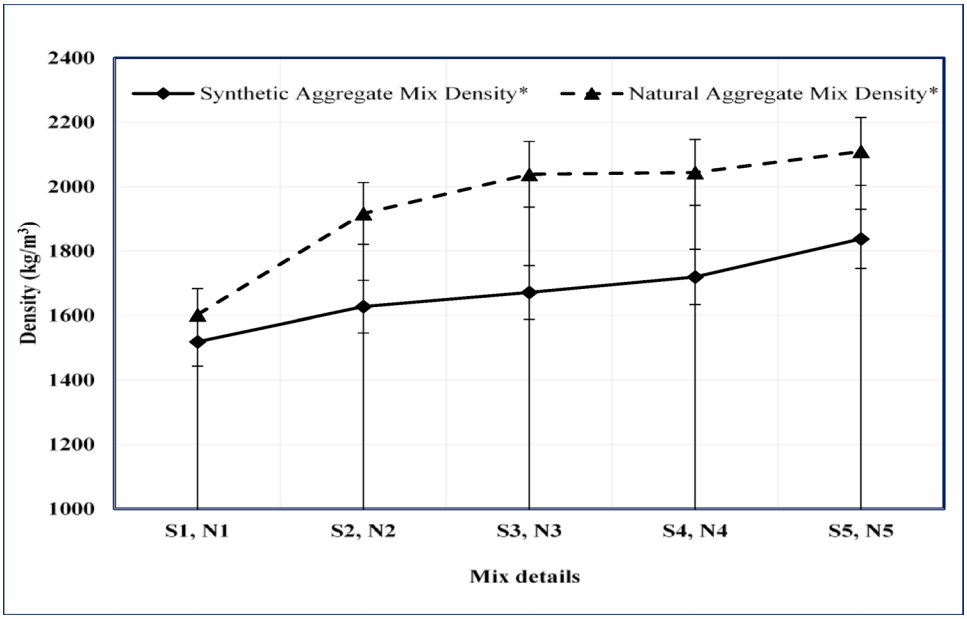


Fig. 4 Synthetic versus natural aggregate dry density of pervious concrete

Table 7 Statistical analysis of density results

Density (kg/m^3)							
Mix ID	Synthetic aggregate mix			Mix ID	Natural aggregate mix		
	Average	SD	COV (%)		Average	SD	COV (%)
S1	1519.0	18.5	1.22	N1	1603.0	35.7	2.23
S2	1628.0	30.0	1.84	N2	1917.0	51.6	2.69
S3	1671.0	109.5	6.55	N3	2039.0	51.5	2.53
S4	1720.0	36.8	2.14	N4	2044.0	36.0	1.76
S5	1838.0	49.5	2.70	N5	2110.0	94.1	4.46

OLS formulations for the slope (b) and intercept (a), as expressed in Eq. (4):

$$b = \frac{\sum (x - \overline{x})\,(y - \overline{y})}{\sum (x - \overline{x})^2}, a = \overline{y} - b\overline{x} \tag{4}$$

In this equation, x and y are the independent and dependent variables, respectively. The regression equations that were generated as a result created predictive models that could estimate the performance of synthetic behaviour from that of natural aggregate [50–52].

To assess model performance, the coefficient of determination (R^2), adjusted coefficient of determination (Adjusted R^2), root mean square error (RMSE), and mean absolute error (MAE) were calculated and reported. These metrics were used solely to evaluate goodness-of-fit and should not be interpreted as evidence of external predictive capability, as independent validation data were not available in the present study.

Results and discussion

Density of geopolymer pervious concrete

The dry density results of the geopolymer pervious concrete mixtures are presented in Fig. 4, while the corresponding statistical summary is provided in Table 7. An increase in dry density was observed with increasing fly ash content for both the SA and NA systems. For the SA mixtures, the dry density increased from 1519 kg/m^3 for the S1 mixture to 1838 kg/m^3 for the S5 mixture. Similarly, the density of the NA mixtures increased from 1603 kg/m^3 to 2110 kg/m^3 over the same range of mixture proportions.

The observed results indicate that higher fly ash contents were associated with increased dry density in both aggregate systems. Similar trends have been reported in previous studies on geopolymer concrete materials, where mixture composition significantly influenced the resulting density values [29, 41].

Across all mixture proportions, the NA mixtures exhibited higher dry density values than the corresponding SA mixtures. The density difference between the two systems ranged from approximately 5 to 20%, depending on the

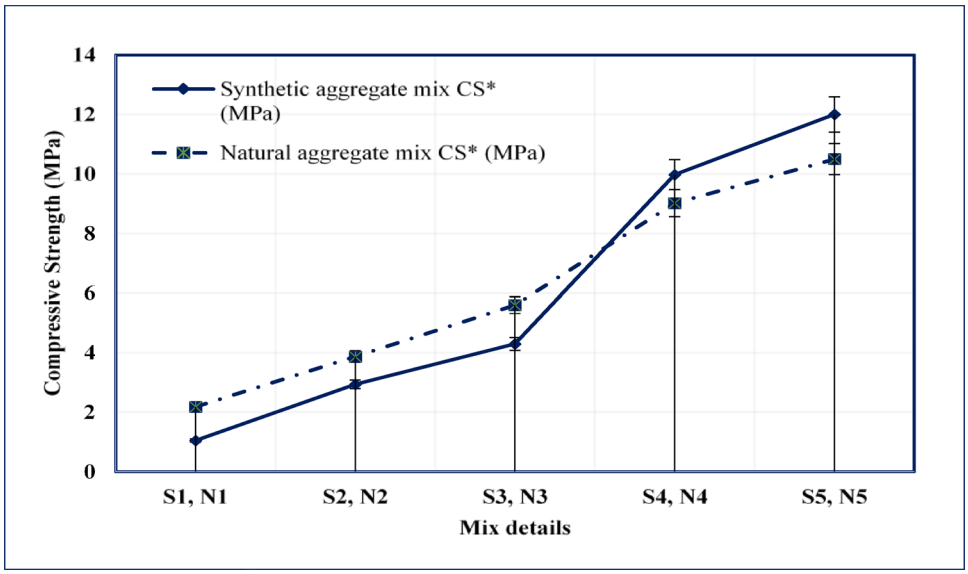


Fig. 5 Compressive strength of synthetic aggregate mix versus natural aggregate mix

Table 8 Statistical analysis of compressive strength

Compressive strength (MPa)							
Mix ID	Synthetic aggregate mix			Mix ID	Natural aggregate mix		
	Average	SD	COV (%)		Average	SD	COV (%)
S1	1.050	0.024	2.29	N1	2.180	0.072	3.29
S2	2.940	0.131	4.44	N2	3.870	0.059	1.52
S3	4.300	0.196	4.55	N3	5.600	0.363	6.48
S4	9.980	0.419	4.19	N4	9.020	0.688	7.63
S5	12.000	0.912	7.60	N5	10.500	0.049	0.47

mixture composition. This behaviour may be associated with the lower specific gravity and bulk density of the engineered synthetic aggregates compared with conventional crushed stone aggregates. Consequently, the incorporation of synthetic aggregates resulted in comparatively lighter concrete mixtures [21, 26, 27].

The statistical analysis presented in Table 6 demonstrates relatively low variability in the density measurements. The coefficient of variation (COV) values ranged from 1.22 to 6.55% for the SA mixtures and from 1.76 to 4.46% for the NA mixtures. All COV values were below 10%, indicating good repeatability and consistency of the experimental measurements. The corresponding standard deviation values also remained within acceptable limits for laboratory-produced pervious concrete mixtures, confirming the reliability of the density results.

Overall, the results demonstrate that both aggregate type and fly ash content influenced the dry density of geopolymer pervious concrete. While the NA mixtures produced higher density values, the SA mixtures yielded comparatively lighter concretes, highlighting the influence of aggregate characteristics on the physical properties of the investigated systems.

Compressive strength behaviour

The compressive strength results of the geopolymer pervious concrete mixtures are presented in Fig. 5, while the corresponding statistical analysis is summarized in Table 7. An overall increase in compressive strength was observed with increasing fly ash content for both the SA and NA systems.

For the SA mixtures, the average compressive strength increased from 1.05 MPa for the S1 mixture to 12.00 MPa for the S5 mixture. Similarly, the compressive strength of the NA mixtures increased from 2.18 to 10.50 MPa over the same range of mixture compositions. The results indicate that the influence of fly ash content on compressive strength was evident in both aggregate systems, although the magnitude of the increase varied among the investigated mixtures.

The statistical analysis presented in Table 8 demonstrates acceptable repeatability of the experimental results. The coefficient of variation (COV) values ranged from 2.29 to 7.60% for the SA mixtures and from 0.47 to 7.63% for the NA mixtures. All COV values remained below 10%, indicating satisfactory consistency among the replicate specimens and confirming the reliability of the measured compressive strength values.

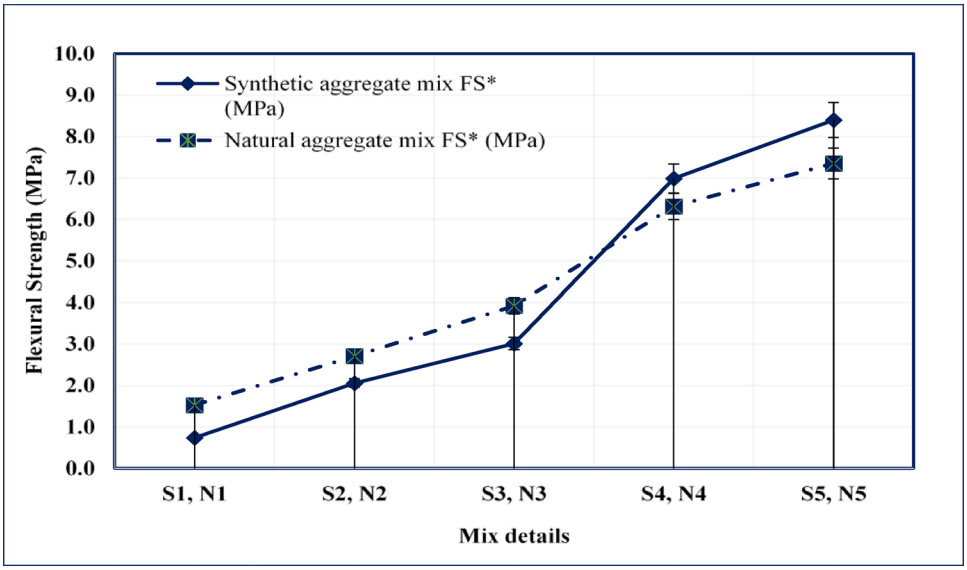


Fig. 6 Flexural strength of synthetic aggregate mix versus natural aggregate mix

Table 9 Statistical analysis of flexural strength

Flexural strength (MPa)							
Mix ID	Synthetic aggregate mix			Mix ID	Natural aggregate mix		
	Average	SD	COV (%)		Average	SD	COV (%)
S1	0.700	0.129	18.46	N1	1.500	0.032	2.16
S2	2.167	0.130	5.99	N2	2.700	0.074	2.74
S3	3.000	0.295	9.84	N3	3.900	0.258	6.62
S4	7.000	0.914	13.06	N4	6.300	0.282	4.48
S5	8.400	0.358	4.26	N5	7.400	0.346	4.68

A comparison between the two aggregate systems shows that the NA mixtures exhibited higher compressive strengths at lower fly ash contents (15FA–25FA), whereas the SA mixtures achieved comparable or higher compressive strengths at higher fly ash contents (30FA–35FA). This observation suggests that aggregate type influenced the strength development behaviour of the geopolymer pervious concrete mixtures. However, the underlying mechanisms governing this behaviour were not directly investigated in the present study and therefore require further microstructural characterization for verification.

The observed compressive strength values fall within the range commonly reported for geopolymer-based pervious concrete materials in the literature [39]. The results demonstrate that both aggregate type and mixture composition significantly influenced compressive strength development. Furthermore, the systematic increase in strength with increasing fly ash content indicates that mixture composition can be used as an effective parameter for tailoring the mechanical performance of geopolymer pervious concrete within the investigated experimental range.

Overall, the compressive strength results confirm that geopolymer pervious concrete incorporating engineered synthetic aggregates can achieve mechanical performance comparable to that of corresponding natural aggregate mixtures, particularly at higher fly ash contents. These findings support the feasibility of utilizing geopolymer-derived synthetic aggregates as an alternative aggregate source in pervious geopolymer concrete systems.

Flexural strength analysis

The flexural strength results of the geopolymer pervious concrete mixtures are presented in Fig. 6, while the corresponding statistical analysis is summarized in Table 9. An overall increase in flexural strength was observed with increasing fly ash content for both the engineered synthetic aggregate (SA) and natural aggregate (NA) systems.

For the SA mixtures, the average flexural strength increased from 0.70 MPa for the S1 mixture to 8.40 MPa for the S5 mixture. Similarly, the flexural strength of the NA mixtures increased from 1.50 to 7.40 MPa over the same range of mixture proportions. The results indicate that higher fly ash contents were associated with improved flexural performance in both aggregate systems.

The statistical analysis presented in Table 8 demonstrates acceptable repeatability of the experimental measurements. The coefficient of variation (COV) values ranged from 4.26 to 18.46% for the SA mixtures and from 2.16 to 6.62% for the NA mixtures. With the exception of the S1

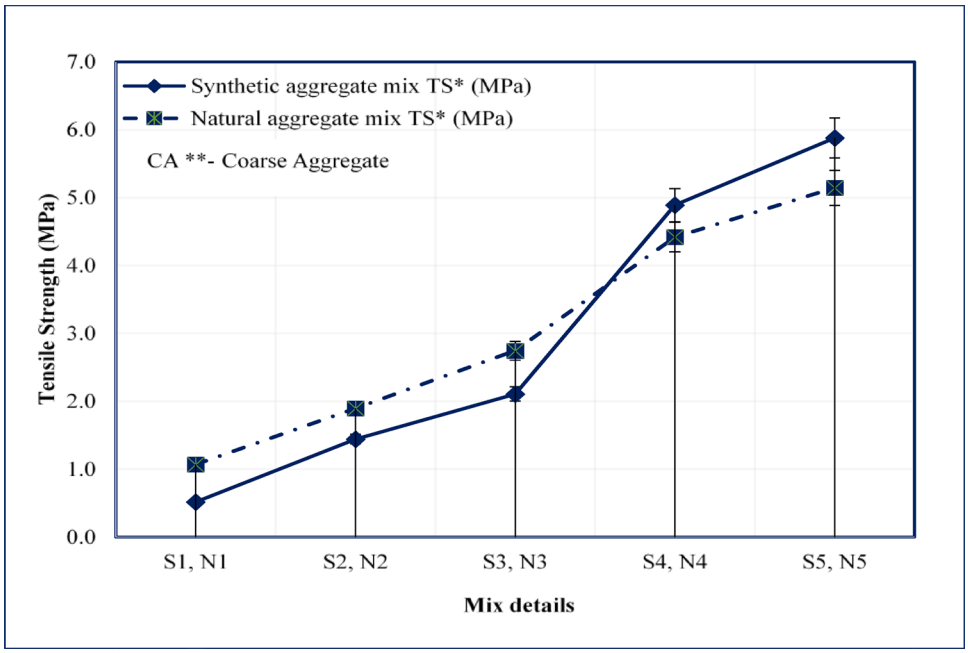


Fig. 7 Tensile strength of synthetic aggregate mix versus natural aggregate mix

Table 10 Statistical analysis of split tensile strength

Split tensile strength (MPa)							
Mix ID	Synthetic aggregate mix			Mix ID	Natural aggregate mix		
	Average	SD	COV (%)		Average	SD	COV (%)
S1	0.500	0.181	36.20	N1	1.100	0.048	4.39
S2	1.400	0.202	14.44	N2	1.900	0.093	4.90
S3	2.100	0.159	7.55	N3	2.700	0.065	2.41
S4	4.900	0.416	8.48	N4	4.400	0.367	8.34
S5	5.900	0.691	11.72	N5	5.100	0.299	5.87

mixture, which exhibited comparatively higher variability, the remaining mixtures showed COV values generally below 15%, indicating satisfactory consistency among the replicate specimens.

A comparison of the two aggregate systems reveals that the NA mixtures exhibited higher flexural strengths at lower fly ash contents (15FA–25FA), whereas the SA mixtures achieved comparable or higher flexural strengths at higher fly ash contents (30FA–35FA). This trend is consistent with the corresponding compressive strength behaviour discussed in Sect. "Compressive strength behaviour". The observed differences suggest that aggregate type and mixture composition both influenced the flexural response of the geopolymer pervious concrete mixtures.

The increase in flexural strength with increasing fly ash content may be associated with changes in the geopolymer binder system reported in previous studies [42–44]. However, because microstructural characterization was not performed in the present investigation, the underlying mechanisms responsible for the observed strength development could not be directly verified and therefore require further study.

Overall, the flexural strength results demonstrate that both aggregate type and fly ash content significantly influenced the bending resistance of geopolymer pervious concrete. The findings further indicate that SA mixtures can achieve flexural performance comparable to, and in some cases exceeding, that of corresponding natural aggregate mixtures within the investigated experimental range.

Split tensile strength behaviour

The splitting tensile strength results of the geopolymer pervious concrete mixtures are presented in Fig. 7, while the corresponding statistical analysis is summarized in Table 10. An overall increase in tensile strength was observed with increasing fly ash content for both the engineered SA and NA systems.

For the SA mixtures, the average splitting tensile strength increased from 0.50 MPa for the S1 mixture to 5.90 MPa for the S5 mixture. Similarly, the tensile strength of the NA mixtures increased from 1.10 to 5.10 MPa over the same range of mixture compositions. At lower fly ash contents (15FA–25FA), the NA mixtures consistently exhibited

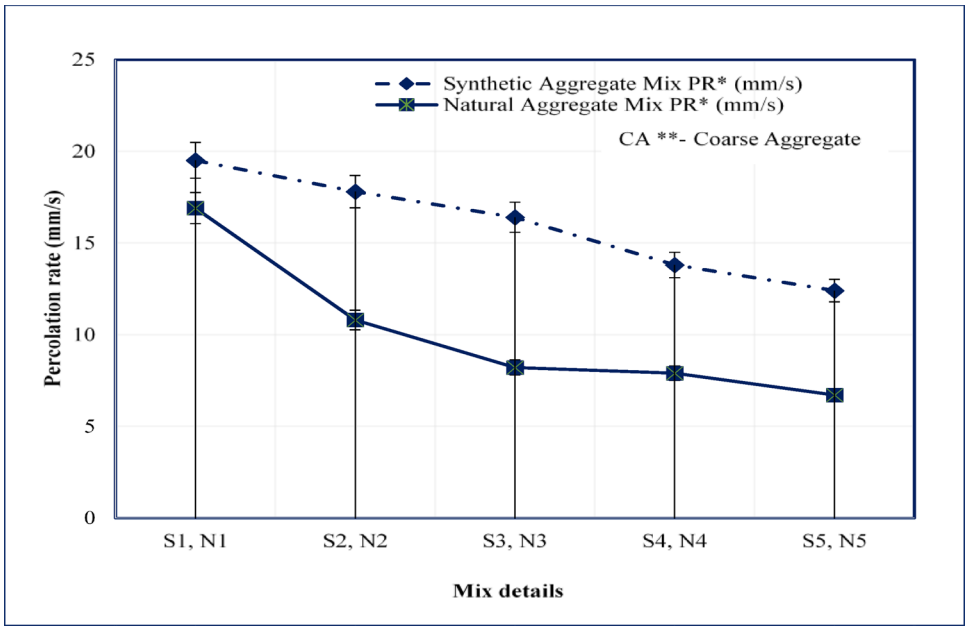


Fig. 8 Percolation rate of synthetic aggregate mix versus natural aggregate mix

Table 11 Statistical analysis of percolation rate

Rate of percolation (mm/s)							
Mix ID	Synthetic aggregate mix			Mix ID	Natural aggregate mix		
	Average	SD	COV (%)		Average	SD	COV (%)
S1	19.500	1.348	6.91	N1	16.900	1.479	8.75
S2	17.800	0.962	5.40	N2	10.800	0.147	1.36
S3	16.400	0.466	2.84	N3	8.200	1.091	13.30
S4	13.800	0.290	2.10	N4	7.900	0.479	6.07
S5	12.400	0.435	3.51	N5	6.700	0.240	3.58

higher tensile strengths than the corresponding SA mixtures. However, at higher fly ash contents (30FA–35FA), the SA mixtures achieved comparable or higher tensile strengths than the NA mixtures.

The statistical analysis presented in Table 9 indicates acceptable repeatability for most mixtures. The coefficient of variation (COV) values ranged from 7.55 to 36.20% for the SA mixtures and from 2.41 to 8.34% for the NA mixtures. The relatively high COV value observed for the S1 mixture may be attributed to the greater influence of local pore distribution and specimen-to-specimen variability at lower strength levels, which is commonly observed in pervious concrete systems. Nevertheless, the overall strength development trend remained consistent across the investigated mixture proportions.

The observed results demonstrate that both aggregate type and fly ash content influenced the tensile strength behaviour of geopolymer pervious concrete. The increase in tensile strength with increasing fly ash content may be associated with changes in the geopolymer binder system reported in previous studies [42, 45, 53]. However, because detailed microstructural characterization was not performed in the present investigation, the underlying mechanisms governing the observed strength development could not be directly verified.

Overall, the results indicate that SA mixtures can achieve tensile strength performance comparable to that of natural aggregate mixtures, particularly at higher fly ash contents. These findings further support the potential use of geopolymer-derived synthetic aggregates in pervious concrete applications.

Percolation rate and hydraulic performance

The percolation rate results of the geopolymer pervious concrete mixtures are presented in Fig. 8, while the corresponding statistical analysis is summarized in Table 11. For both aggregate systems, the percolation rate decreased with increasing fly ash content.

For the SA mixtures, the average percolation rate decreased from 19.5 mm/s for the S1 mixture to 12.4 mm/s for the S5 mixture. A similar trend was observed for the NA mixtures, where the percolation rate decreased from 16.9 to 6.7 mm/s across the same mixture range. The results indicate that higher fly ash contents were associated with lower percolation rates in both aggregate systems.

The statistical analysis presented in Table 10 demonstrates good repeatability of the hydraulic measurements. The coefficient of variation (COV) values ranged from 2.10 to 6.91% for the SA mixtures and from 1.36 to 13.30% for the NA mixtures. With the exception of the N4 mixture, which exhibited comparatively higher variability, all mixtures showed COV values below 10%, indicating satisfactory consistency among replicate specimens.

A comparison of the two aggregate systems reveals that the SA mixtures consistently exhibited higher percolation rates than the corresponding NA mixtures throughout the investigated range of fly ash contents. The difference in hydraulic performance may be related to the physical characteristics of the aggregate systems and their influence on the resulting pore structure of the pervious concrete. However, as direct measurements of porosity, void connectivity, or microstructural features were not conducted in the present study, the specific mechanisms responsible for the observed behaviour could not be conclusively established.

The reduction in percolation rate with increasing fly ash content observed in both aggregate systems suggests that mixture composition significantly influenced hydraulic performance. Similar trends have been reported in previous studies on pervious geopolymer concrete materials [41–45].

Overall, the results demonstrate that aggregate type and fly ash content both affected the hydraulic behaviour of geopolymer pervious concrete. While the SA mixtures maintained higher percolation rates across all mixture proportions, both aggregate systems exhibited sufficient permeability characteristics consistent with the intended function of pervious concrete materials.

Comparative performance of synthetic and natural aggregate pervious concrete

Density, compressive strength, flexural strength, and splitting tensile strength of geopolymer pervious concrete produced using SA and NA is illustrated in Figs. 9 and 10. The results demonstrate that both aggregate type and mixture composition influenced the overall performance of the investigated concrete systems.

As shown in Fig. 9, dry density increased with increasing fly ash content for both aggregate systems. The density of the SA mixtures increased from 1519 kg/m^3 for the S1 mixture to 1838 kg/m^3 for the S5 mixture, whereas the density of the NA mixtures increased from 1603 to 2110 kg/m^3 over the same mixture range. Throughout the investigation, the NA mixtures consistently exhibited higher density values than the corresponding SA mixtures, reflecting the influence of aggregate characteristics on the physical properties of the concrete [29, 41]..

A corresponding increase in compressive strength was observed with increasing fly ash content. The compressive strength of the SA mixtures increased from 1.05 to 12.00 MPa, while the NA mixtures increased from 2.18 to 10.50 MPa. At lower fly ash contents, the NA mixtures exhibited higher compressive strength values; however, the SA mixtures achieved comparable or higher strengths at the higher fly ash contents investigated. These results indicate that the performance gap between the two aggregate systems decreased as the fly ash content increased.

Figure 10 illustrates the relationship between density, flexural strength, and splitting tensile strength. Similar to the compressive strength results, both flexural and tensile strengths increased with increasing fly ash content. The flexural strength of the SA mixtures increased from 0.70 to

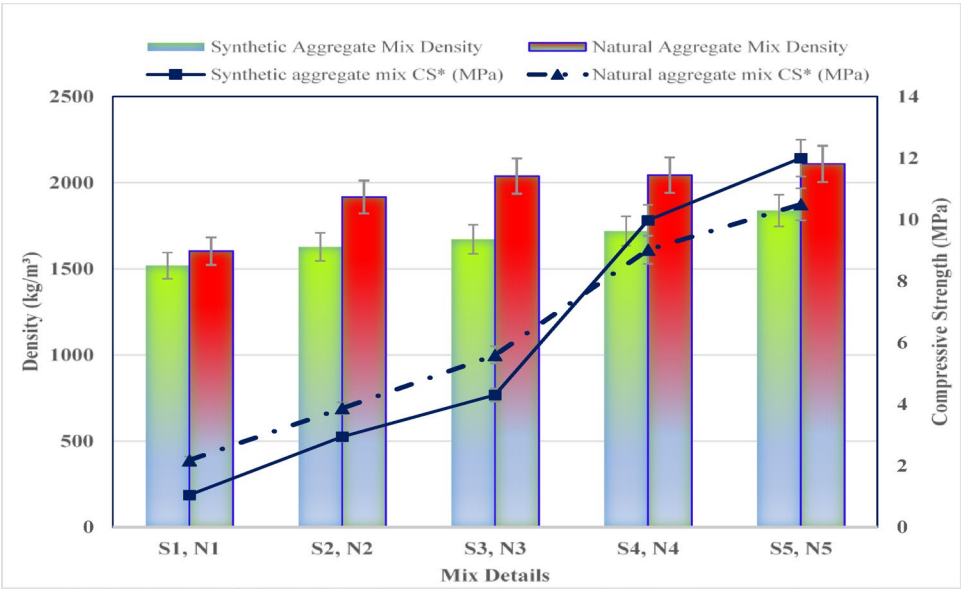


Fig. 9 Density and compressive strength of synthetic versus natural aggregate mix

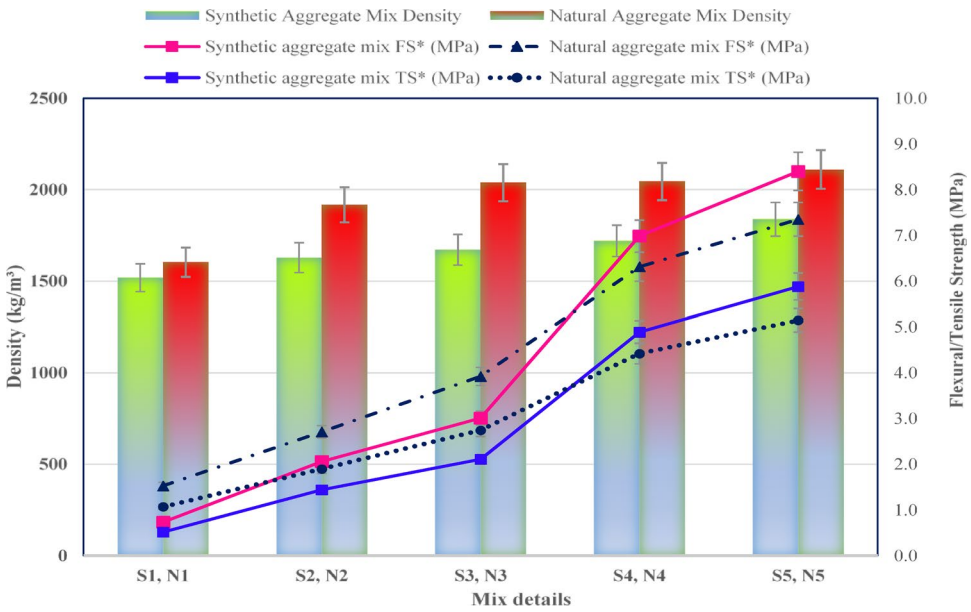


Fig. 10 Density, flexural and tensile strength of synthetic versus natural aggregate mix

Table 12 Performance ranking of investigated mixtures

Category	Synthetic aggregate system	Natural aggregate system
Highest density	S5	N5
Highest compressive strength	S5	N5
Highest flexural strength	S5	N5
Highest splitting tensile strength	S5	N5
Highest percolation rate	S1	N1

8.40 MPa, while the NA mixtures increased from 1.50 to 7.40 MPa. Likewise, the splitting tensile strength increased from 0.50 to 5.90 MPa for the SA mixtures and from 1.10 to 5.10 MPa for the NA mixtures. The results indicate that the SA mixtures achieved flexural and tensile strengths comparable to, and in some cases exceeding, those of the corresponding NA mixtures at higher fly ash contents [20, 21, 54].

The results further reveal positive relationships among compressive strength, flexural strength, and splitting tensile strength. Mixtures exhibiting higher compressive strengths generally demonstrated higher flexural and tensile strengths, indicating consistent mechanical performance trends across the investigated properties [55]. These observed relationships support the exploratory regression analyses presented in Sect. "Exploratory regression modelling for mechanical and hydraulic properties".

Overall, the comparative assessment demonstrates that the NA mixtures generally produced higher density values, whereas the SA mixtures achieved comparable mechanical performance at higher fly ash contents while maintaining lower density. The findings suggest that engineered synthetic aggregates derived from geopolymer materials can serve as a viable alternative to natural aggregates in geopolymer pervious concrete systems within the investigated experimental range.

Table 12 provides a summary of the performance characteristics of the investigated mixtures. In general, mixtures containing higher fly ash contents exhibited improved mechanical properties, whereas mixtures containing lower fly ash contents demonstrated higher percolation rates. This trend highlights the balance between mechanical performance and hydraulic functionality that is characteristic of pervious concrete systems. The identified mixtures may therefore serve as useful reference compositions for future investigations and practical mix selection. Among the investigated mixtures, SA20 demonstrated a favourable combination of mechanical performance and hydraulic behaviour within the investigated experimental range. However, because no quantitative multi-criteria performance index was established in the present study, no overall ranking of mixture performance is proposed.

Exploratory regression modelling for mechanical and hydraulic properties

To further examine the relationships between the performances of the SA and NA systems, exploratory regression analyses were conducted using the experimental results obtained in this study. The objective of the analysis was to investigate whether consistent relationships existed between corresponding properties of the two aggregate systems and to assess the suitability of simple linear regression for describing the observed trends within the investigated dataset [50–52].

The developed regression equations were derived using ordinary least-squares (OLS) analysis and were evaluated

through comparisons between actual and estimated values. The models are intended to describe the observed experimental relationships and should not be interpreted as universally applicable predictive tools because independent validation data were not available.

Exploratory regression analysis of compressive strength

The regression relationships between the compressive strengths of the SA and NA mixtures are expressed by Eqs. (5) and (6):

$$CS_s = -1.1434 + 1.3938\,(CS_n) \tag{5}$$

$$CS_n = 1.6436 + 0.7427\,(CS_s) \tag{6}$$

Figure 11 compares the measured and estimated compressive strength values. The estimated values followed the overall trend of the experimental data across the investigated fly ash contents. The regression model captured the increase in compressive strength observed for both aggregate systems and demonstrated a strong linear relationship between the corresponding compressive strengths of the SA and NA mixtures.

Although good alignment was observed within the investigated dataset, the model should be regarded as exploratory because the analysis was performed using a limited number of mixture compositions. Therefore, the equation is intended primarily for trend interpretation within the studied experimental range.

Exploratory regression analysis of flexural strength

The regression relationships between the flexural strengths of the SA and NA mixtures are expressed by Eqs. (7) and (8):

$$FS_s = 1.3352\,(FS_n) - 1.5815 \tag{7}$$

$$FS_n = 0.7401\,(FS_s) + 1.2219 \tag{8}$$

The comparison between measured and estimated flexural strengths is presented in Fig. 12. The estimated values closely followed the experimental results across the investigated mixture compositions, indicating a strong linear association between the flexural performances of the two aggregate systems. The agreement between measured and estimated values suggests that flexural strength trends observed in one aggregate system were reflected in the corresponding system.

Exploratory regression analysis of splitting tensile strength

The regression relationships describing the splitting tensile strength behaviour are given by Eqs. (9) and (10):

$$TS_n = 0.7183\,(TS_s) + 0.9139 \tag{9}$$

$$TS_s = 1.3785\,(TS_n) - 1.2305 \tag{10}$$

Figure 13 presents the comparison between measured and estimated splitting tensile strengths. The estimated values showed close agreement with the experimental data throughout the investigated range of fly ash contents. The

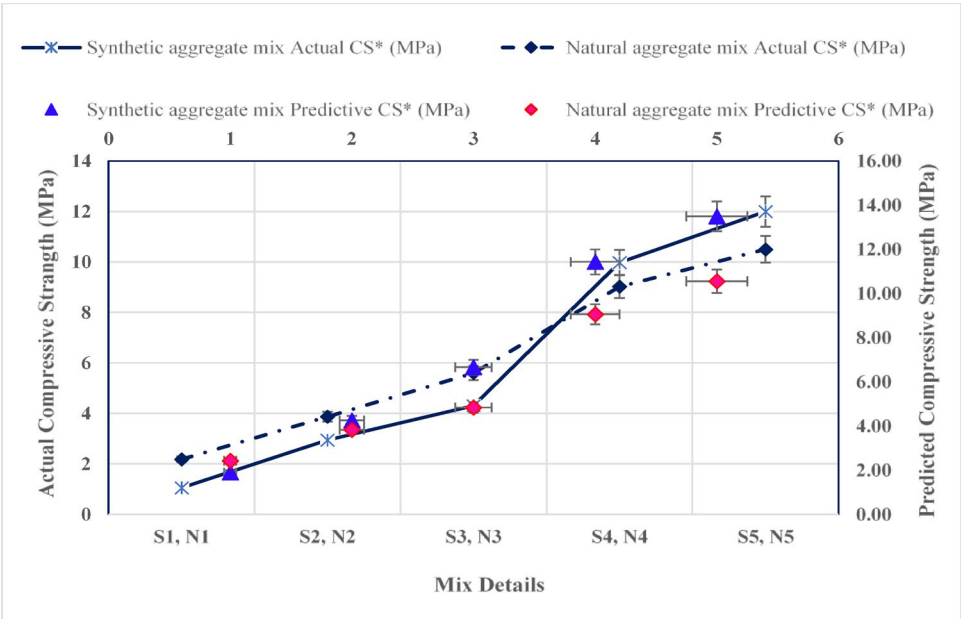


Fig. 11 Predicted versus actual compressive strength

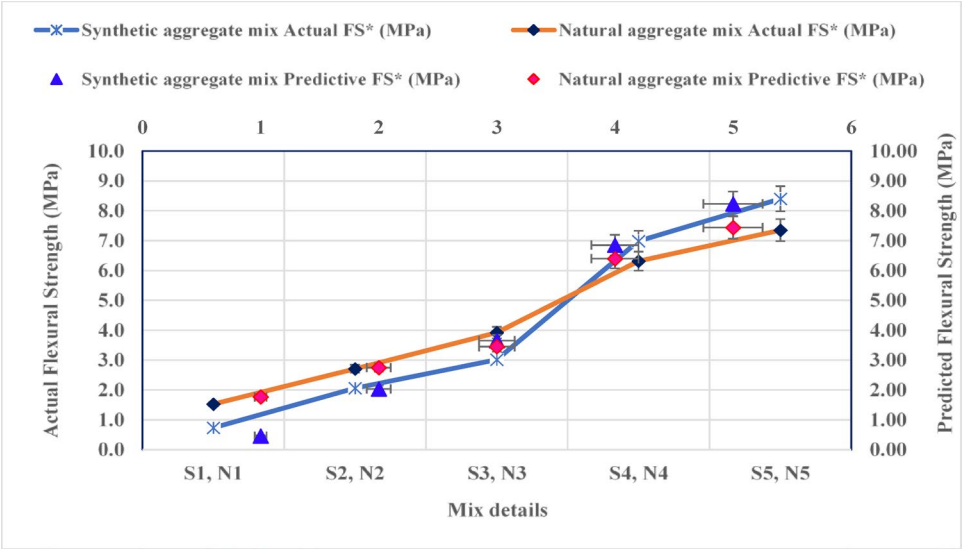


Fig. 12 Predicted versus actual flexural strength

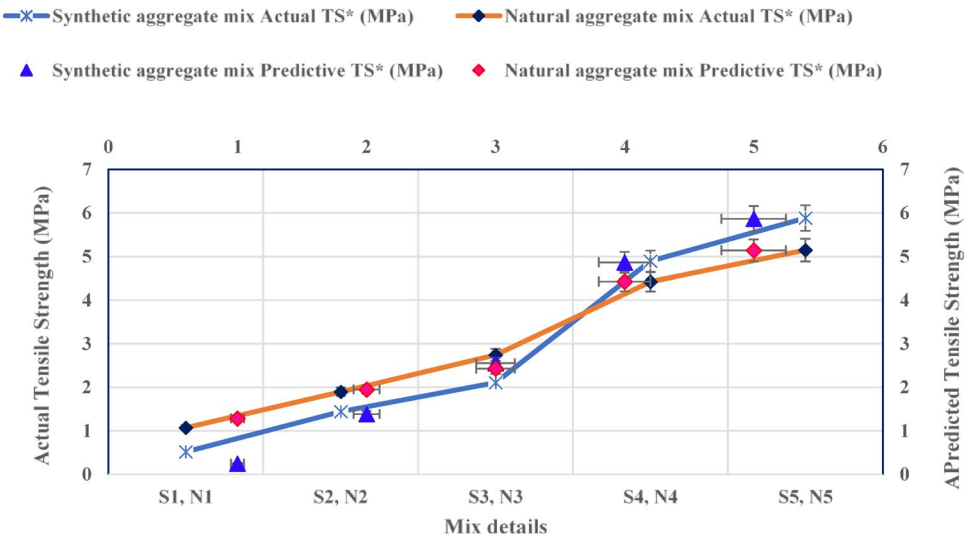


Fig. 13 Predicted versus actual tensile strength

results indicate a strong linear relationship between the tensile strength performances of the SA and NA mixtures and further support the consistency of the observed mechanical property trends.

Exploratory regression analysis of percolation rate

The regression relationships developed for the percolation rate are expressed by Eqs. (11) and (12):

$$PR_s = 0.6200\,(PR_n) + 9.7178 \tag{11}$$

$$PR_n = 1.2371\,(PR_s) - 9.6696 \tag{12}$$

The comparison between measured and estimated percolation rates is shown in Fig. 14. The estimated values generally followed the experimental trends observed for both aggregate systems. Greater scatter was observed compared with the mechanical property models, reflecting the increased variability typically associated with hydraulic measurements in pervious concrete materials. Nevertheless, the regression model adequately described the overall relationship between the percolation rates of the SA and NA mixtures within the investigated dataset.

Statistical performance of the exploratory regression models

Table 13 summarizes the statistical indicators used to evaluate the exploratory regression models.

The flexural strength and splitting tensile strength models exhibited the strongest goodness-of-fit, with R^2 values exceeding 0.98 and comparatively low RMSE and MAE values. The compressive strength model also demonstrated a strong linear relationship ($R^2 = 0.9053$), whereas the percolation rate model showed a comparatively lower coefficient

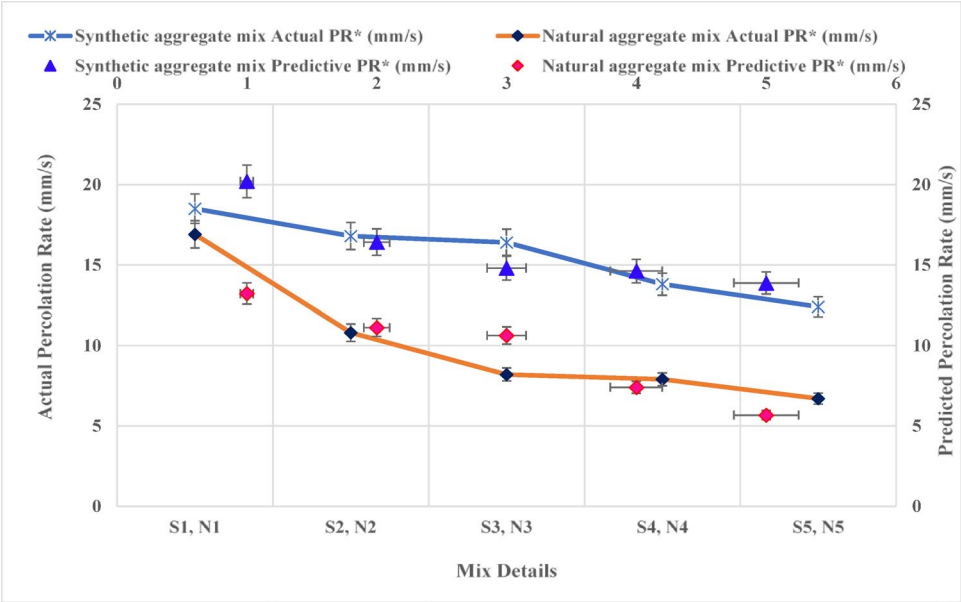


Fig. 14 Predicted versus actual percolation rate

Table 13 Statistical performance indicators of exploratory regression models

Property	R^2	Adjusted R^2	RMSE	MAE
Compressive strength	0.9053	0.8935	1.1390	0.8600
Flexural strength	0.9879	0.9863	0.2868	0.2170
Splitting tensile strength	0.9883	0.9869	0.1960	0.1380
Percolation rate	0.8236	0.8016	1.7100	1.3920

of determination (R^2 = 0.8236), indicating greater variability in the hydraulic response data.

Overall, the statistical indicators suggest that the developed equations adequately describe the relationships observed within the experimental dataset. However, because the models were developed using a limited number of mixtures and were not independently validated, they should be considered exploratory tools for trend analysis rather than generalized predictive models. Future studies incorporating larger datasets and independent validation experiments are recommended to improve model robustness and broader applicability.

Limitations and future research direction

Although the present study demonstrates the feasibility of utilizing engineered synthetic geopolymer aggregates in pervious geopolymer concrete, several limitations should be acknowledged.

First, the investigation focused primarily on the physical, mechanical, and hydraulic properties of the developed mixtures. Direct microstructural characterization techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), mercury intrusion porosimetry (MIP), or image-based pore analysis were not conducted. Consequently, the mechanisms governing aggregate–binder interactions, pore structure evolution, and geopolymer reaction products could not be directly verified.

Second, porosity, void ratio, and pore connectivity were not experimentally quantified. Therefore, interpretations regarding hydraulic behaviour were based on measured percolation rates rather than direct pore-structure characterization.

Third, the regression models developed in this study were based on a limited experimental dataset and were evaluated only using the available mixtures. Independent validation datasets were not available; therefore, the proposed equations should be regarded as exploratory models intended for trend analysis within the investigated experimental domain.

Fourth, the study was conducted under laboratory conditions and did not include long-term durability assessments such as abrasion resistance, freeze–thaw resistance, clogging resistance, chemical durability, cyclic loading, or field-scale performance evaluation.

Finally, although potential applications such as permeable pavement and drainage-related infrastructure are envisioned, prototype-scale structural validation was beyond the scope of the present investigation.

Future research should focus on comprehensive microstructural characterization, quantitative porosity analysis, advanced durability assessment, expanded experimental datasets for model validation, and field-scale demonstrations to further establish the long-term performance and practical applicability of geopolymer-derived synthetic aggregate pervious concrete systems.

Conclusions

The present study evaluated the influence of geopolymer-based engineered synthetic aggregates on the mechanical and hydraulic performance of geopolymer pervious concrete. Based on the experimental results obtained within the investigated range of mixture compositions, the following conclusions can be drawn:

(1) SA mixtures exhibited mechanical and hydraulic performance trends comparable to those of corresponding natural aggregate mixtures under identical geopolymer binder conditions.
(2) Increasing fly ash content generally enhanced compressive, flexural, and splitting tensile strengths while reducing percolation rate.
(3) Positive correlations were observed among compressive strength, flexural strength, and splitting tensile strength, indicating consistent mechanical performance trends across the investigated mixtures.
(4) Exploratory regression models demonstrated satisfactory agreement with the experimental data and may be useful for preliminary trend assessment within the investigated composition range.
(5) The recalculated statistical parameters confirmed satisfactory experimental repeatability, with most coefficient of variation values remaining within acceptable ranges for concrete materials testing.
(6) Although the investigated material demonstrated promising mechanical and hydraulic characteristics, direct porosity characterization, microstructural analysis, durability assessment, and independent model validation were beyond the scope of the present study and should be addressed in future research.

Overall, the study provides preliminary evidence supporting the feasibility of incorporating geopolymer-based engineered synthetic aggregates into pervious geopolymer concrete systems and establishes a foundation for future optimization and application-oriented investigations.

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Data availability All data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no known conflict of financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval This study did not involve human participants or animal testing. All experimental procedures complied with institutional environmental and safety regulations.

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