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Engineering characteristics of agro-residue–based geopolymer concrete with fibre reinforcement

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The creation of eco-friendly construction materials by utilising agro-industrial by-products presents a promising approach to lowering the carbon emissions of the building industry. This research explores the engineering behaviour of geopolymer concrete formulated with sugarcane bagasse ash, rice husk ash, and cow dung ash as aluminosilicate sources, further strengthened with basalt fibres in varying amounts (0–2.5%). A wide range of experiments was performed to assess mechanical performance (compressive, flexural, and split tensile strengths) and durability characteristics (chloride ion penetration, water absorption, and resistance to acid attack) over curing periods extending to 180 days. Results exhibited a clear parabolic relationship with fibre content, identifying an optimum dosage near 1% basalt fibre. The compressive strength increased from 50 to 62 MPa (24% improvement), flexural strength from 4.4 to 5.8 MPa (32% increase), and split tensile strength from 3.7 to 4.8 MPa (30% gain) at 180 days. Durability indicators also improved at the optimum fibre dosage: water absorption decreased from 8 to 5%, acid attack-induced mass loss reduced from 38 to 6%, and RCPT values dropped from 3100 to 1600 C, shifting chloride penetrability from moderate to low. However, fibre contents above 1.5% led to reduced workability, fibre clustering, and increased permeability. ANOVA confirmed the dominance of the quadratic fibre effect, with Fibre² contributing 50–62% of the total variation across responses. Overall, the study demonstrates that basalt fibre–reinforced agro-waste geopolymer concrete not only satisfies structural and durability requirements but also advances sustainable construction by converting waste into resources and reducing dependency on Portland cement.

Keywords Agro-waste valorisation, Geopolymer concrete, Fibre reinforcement, Sustainable construction, Strength and durability, Circular economy, Low-carbon building materials

The increasing demand for sustainable and environmentally friendly construction materials has intensified the search for alternatives to Ordinary Portland Cement (OPC), which is responsible for a significant portion of global carbon emissions^{1–4}. Geopolymer concrete has emerged as a promising low-carbon alternative, synthesised through the alkali activation of aluminosilicate-rich materials^{5–10}. While conventional geopolymer research has primarily focused on industrial by-products such as fly ash and GGBFS^{11–19}, this study introduces a novel approach by utilizing a ternary blend of agricultural and organic wastes viz: sugarcane bagasse ash (SCBA), rice husk ash (RHA), and cow dung ash (CDA), as the primary binder material. These wastes, rich in silica and alumina, offer a viable and eco-friendly solution by reducing landfill burden and promoting resource circularity. In addition, the incorporation of basalt fibre, known for its high tensile strength and chemical stability^{14,20–22}, is explored to enhance the mechanical and durability performance of the developed geopolymer concrete.

The performance of geopolymer concrete is significantly influenced by several processing and environmental factors, among which the curing regime, type and concentration of alkaline activator, and precursor composition play critical roles. The curing temperature and duration directly impact the rate of geopolymerization, where elevated temperatures often accelerate the dissolution of aluminosilicate species and enhance the early-age strength development^{14,23–28}. Additionally, the concentration of sodium hydroxide (NaOH) solution influences the alkalinity of the activating medium; higher molarity enhances the reactivity of precursors but may also lead to rapid setting and reduced workability^{29–31}. The choice of alkaline activator, such as NaOH, sodium silicate, or their combinations, affects the polymerization kinetics and the final gel structure, thereby influencing mechanical

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and durability properties^{32–34}. Other factors such as the liquid-to-solid ratio, precursor fineness, Si/Al ratio, and mixing conditions also govern the microstructural development, pore structure, and overall performance of the hardened geopolymer matrix^{35–38}. Hence, optimizing these parameters is essential to achieve a balance between mechanical strength, workability, and long-term durability in geopolymer concrete systems.

The novelty of this research lies in the combined use of three distinct agro-industrial waste materials in a geopolymer matrix reinforced with basalt fibre, a combination not widely studied in existing literature. The investigation comprehensively evaluates the effect of varying basalt fibre content (0–2.5%) on workability, strength characteristics, and long-term durability. The study fills a critical research gap by not only proposing a sustainable binder system but also optimising fibre dosage to balance fresh and hardened state performance.

The objectives of this research are fivefold: first, to develop geopolymer concrete using a ternary blend of SCBA, RHA, and CDA as a cement replacement material; second, to incorporate basalt fibre at varying dosages and assess its impact on slump retention and workability; third, to evaluate the mechanical performance through compressive strength, flexural strength, and split tensile strength at 7, 28, 90, and 180 days; fourth, to assess the durability of the mixes using water absorption, weight loss under chemical attack, and rapid chloride penetration tests (RCPT); and finally, to identify the optimal mix that offers the best combination of strength and durability for potential application in sustainable construction. Through this integrated approach, the study contributes to the advancement of green building materials while promoting waste utilization, circular economy principles, and climate-resilient infrastructure.

Materials used

The materials utilized in this study for the development of GPC included a combination of industrial and agricultural by-products, chemical activators, and reinforcing agents. SCBA (specific surface area of 23 m²/g), RHA (specific surface area of 40 m²/g), CDA (specific surface area of 39 m²/g) were employed as the primary aluminosilicate source materials due to their high silica and alumina contents. These ashes were obtained through controlled combustion, followed by sieving to ensure uniform particle size and reactivity. The alkaline activator solution was prepared using a mixture of sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃), with the NaOH solution formulated at 16 molar concentrations. The ratio of sodium silicate to sodium hydroxide was maintained constant to ensure consistency in gel formation across mixes. Basalt fibres, derived from volcanic rock processing, were incorporated in different dosages (ranging from 0.1 to 2.5% by weight of binder) to enhance the mechanical strength, ductility, and crack resistance of the geopolymer matrix. Crushed granite with a maximum size of 20 mm and locally sourced river sand were used as coarse and fine aggregates, respectively, conforming to IS: 2386 and IS:383 (2016) specifications. Water was used for the preparation of the alkaline solutions and mixing to prevent any impurities from affecting the chemical reactions. All raw materials were characterised for their chemical and physical properties provided in Table 1, and these tests were done by Raicon Labs Sonepat, to confirm their suitability for geopolymer concrete production. Figure 1 shows the grading curves of the materials.

Methodology

The experimental methodology was systematically designed to develop and evaluate basalt fibre-reinforced geopolymer concrete using a ternary blend of agro-industrial ashes. The process included material preparation, mix design, casting, curing, and comprehensive testing of both fresh and hardened properties. Initially, the binder materials such as SCBA, RHA, and CDA were collected, oven-dried to remove moisture, and sieved through a 75 µm mesh to ensure uniform particle size distribution. The ashes were combined in a fixed ratio of 40:30:30 (SCBA:RHA: CDA) by weight. Basalt fibres (12 mm in length) were incorporated at varying dosages of 0%, 0.1%, 0.5%, 1%, 1.5%, 2%, and 2.5% by weight of the the GPC to assess their influence on performance

Physical and chemical properties	SBA	RHA	CDA	Basalt fibres
Size (mm)	–	–	–	12 mm
Fineness (Passing 45 µm)	3	3	3.3	–
Specific gravity (kg/cm ³)	2.31	2.14	2.2	2.6
Al ₂ O ₃ (%)	9	0.18	18	18
SiO ₂ (%)	64	90	60	53
CaO (%)	11	0.7	9.5	4.8
Fe ₂ O ₃ (%)	0.6	0.1	3.5	9
MgO (%)	4.5	–	–	5
Na ₂ O (%)	1.7	–	–	6.2
TiO ₂ (%)	0.1	–	–	2
FeO (%)	–	–	–	–
SO ₃ (%)	–	1.8	–	–
K ₂ O (%)	4	–	–	–
P ₂ O ₅ (%)	1.1	–	–	–
LOI (%)	2	3.12	–	–
Others (%)	2	4.78	9	2.27

Table 1. Physical and chemical properties of materials used.

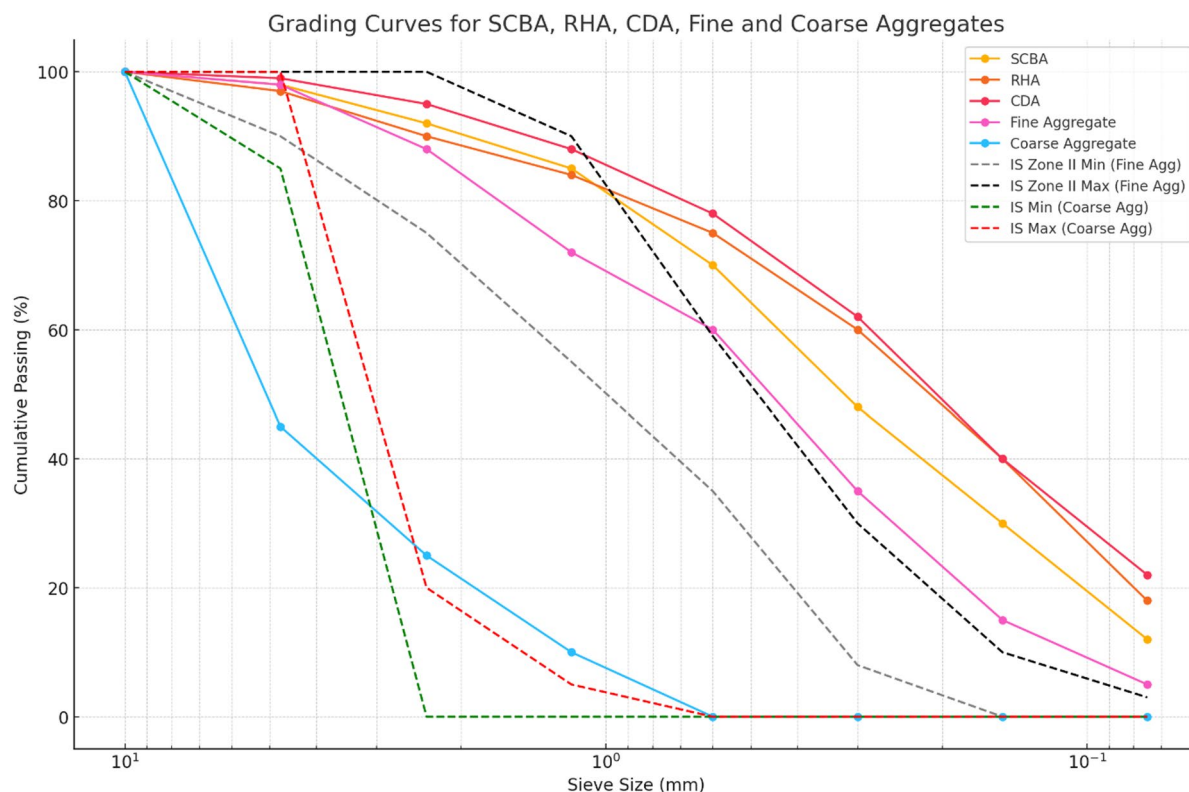


Fig. 1. Grading curves of the materials.

characteristics. The alkaline activator solution was prepared by mixing 16 M sodium hydroxide solution with sodium silicate in a ratio of 1:2.5 by weight. This solution was prepared 24 h in advance to allow for thermal stabilisation and proper dissolution. Dry mixing of ashes, aggregates, and fibres was mixed for 2 min, followed by the gradual addition of the activator solution and further mixing for another 5 min to achieve a uniform GPC matrix. Concrete specimens were cast in steel moulds of standard sizes for different tests: 100 × 100 × 100 mm cubes for compressive strength, 100 × 100 × 500 mm beams for flexural strength, and 100 × 200 mm cylinders for split tensile strength and RCPT.

The fresh properties were evaluated immediately after mixing using the slump cone test to assess workability. Specimens were demoulded after 24 h and cured at elevated temperature for 48 h followed by ambient curing temperature ($27 \pm 2^\circ\text{C}$) for 7, 28, 90, and 180 days. Mechanical tests, including compressive, split tensile, and flexural strength, were conducted as per IS 516:2018. Durability tests involved water absorption measurement (as per ASTM C642), weight loss under acid exposure (12-week immersion in 5% H_2SO_4 solution), and Rapid Chloride Penetration Test (RCPT) following ASTM C1202 to assess chloride ion permeability. All results were compared across different mixes to determine the optimum fibre dosage that enhances strength and durability without compromising workability. The methodology ensured a robust and replicable approach to validating the performance of sustainable geopolymers derived from agricultural waste and basalt fibre reinforcement^{39–41}. Table 2 and Fig. 2 show the mix design and some images from experimentation of the geopolymer blends.

Results and discussion

This section explains the influence of various industrial and agro-waste constituents on the strength development, permeability resistance, and overall performance of the synthesized geopolymer concrete.

Workability

The slump retention behaviour of various GPC mixes incorporating SCBA, RHA, CDA, and basalt fibres is illustrated in the Fig. 3. SRCB0 represents the control mix with no basalt fibre, while SRCB-0.1 to SRCB-2.5 represent mixes with increasing basalt fibre content (from 0.1% to 2.5%). SRCB-1, denotes a geopolymer mix composed of 40% SCBA, 30% RHA, 30% CDA, and 1% basalt fibre, with similar proportions applied to the other respective fibre dosages. The results demonstrate a consistent decline in slump across all mixes over time, reflecting the expected loss in workability due to ongoing polymerization reactions and water loss through evaporation^{42–45}. At the initial time (0 min), all mixes exhibit relatively high slump values, indicating good fresh-state workability. However, as the time interval extends from 0 to 80 min, there is a marked reduction in slump values for all mixes, with more pronounced declines observed in mixes containing higher percentages of basalt fibre. Specifically, SRCB-2 and SRCB-2.5 exhibit the highest slump reductions, likely due to increased

Mix	SRCB0	SRCB-0.1	SRCB-0.5	SRCB-1	SRCB-1.5	SRCB-2	SRCB-2.5
RHA (kg/m ³)	150	150	150	150	150	150	150
SBA (kg/m ³)	200	200	200	200	200	200	200
CDA (kg/m ³)	150	150	150	150	150	150	150
Basalt Fibres (kg/m ³)	0	2.64	13.2	26.4	39.6	52.8	66
Coarse Aggregates (kg/m ³)	1025	1025	1025	1025	1025	1025	1025
Fine Aggregates (kg/m ³)	556	556	556	556	556	556	556
Na ₂ SiO ₃ / NaOH	2.0	2.0	2.0	2.0	2.0	2.0	2.0
NaOH (kg/m ³)	67	67	67	67	67	67	67
Alkaline Activator/binder content	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Na ₂ SiO ₃ (kg/m ³)	133	133.33	133.33	133.33	133.33	133.33	133.33
Superplasticizer (kg/m ³)	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Extra water (kg/m ³)	30.0	30.0	30.0	30.0	30.0	30.0	30.0
NaOH (M)	16	16	16	16	16	16	16

Table 2. Mix proportions.

fibre content causing internal friction and restricting flowability^{14,20–22}. SRCB-0.5 and SRCB-1 maintain better slump retention compared to mixes with higher fibre dosages, suggesting that moderate incorporation of basalt fibres enhances structural cohesion without significantly compromising workability. In contrast, the control mix (SRCB0), which contains no fibre, retains higher slump across the entire period, indicating minimal resistance to flow but potentially lacking in post-setting performance benefits like crack resistance or tensile reinforcement^{21,46–49}. These findings suggest that while the inclusion of basalt fibres can enhance mechanical properties and durability, excessive fibre content can adversely affect the workability of geopolymer concrete. Therefore, an optimal dosage around 0.5–1% basalt fibre appears to provide a balanced trade-off between fresh state workability and long-term performance enhancements, supporting the development of more sustainable and high-performance geopolymer systems using agricultural and organic waste by-products.

Compressive strength

Figure 4 illustrates the compressive strength development of various geopolymer concrete mixes. Compressive strength was evaluated at 7, 28, 90, and 180 days to assess both early-age and long-term performance. The results demonstrate that compressive strength increases with curing time for all mixes, reflecting the progressive geopolymerization and structural densification over time^{34,50–54}. The control mix (SRCB0), which contains no basalt fibre, reaches approximately 50 MPa at 180 days, indicating a good base performance due to the synergistic reactivity of the ternary ash blend^{6,8,34,55,56}. With the addition of basalt fibre, the compressive strength shows a marked improvement up to SRCB-1, which achieves the highest compressive strength at all curing ages, peaking at over 62 MPa at 180 days. This enhancement can be attributed to the microcrack-bridging ability and confinement effect of basalt fibres, which improve the load-bearing capacity and matrix integrity of the concrete^{57,58}. Beyond 1% fibre content, however, a noticeable decline in compressive strength is observed. Mixes SRCB-1.5, SRCB-2, and especially SRCB-2.5 show reduced strength values, particularly at early ages. This reduction is likely due to fibre agglomeration, increased porosity, and reduced workability leading to inadequate compaction and weaker interfacial bonding^{14,20,45,59,60}. The lowest performance is recorded for SRCB-2.5, which remains below 40 MPa even after 180 days. Therefore, the results confirm that the inclusion of basalt fibre up to an optimal dosage of 1% significantly enhances the compressive strength of geopolymer concrete derived from agricultural and organic wastes.

Flexural strength

Figure 5 presents the flexural strength development of GPC mixes (SRCB0 to SRCB-2.5). Flexural strength was assessed at 7, 28, 90, and 180 days to evaluate both short-term and long-term flexural performance. Across all mixes, flexural strength increases steadily with curing time, affirming the continued polymerisation and structural enhancement in the geopolymer matrix^{37,61,62}. The control mix (SRCB0), without any basalt fibre, achieves a maximum flexural strength of approximately 4.4 MPa at 180 days. As basalt fibre is introduced, a significant improvement in flexural strength is observed, particularly in SRCB-0.5 and SRCB-1, which outperform all other mixes. SRCB-1 records the highest flexural strength of nearly 5.8 MPa at 180 days, indicating that 1% basalt fibre content optimally contributes to crack-bridging, load distribution, and energy absorption mechanisms within the composite^{34,63,63–66}. Although SRCB-1.5 also performs well, showing only a slight difference compared to SRCB-1, further increases in fibre content to 2% and 2.5% result in a decline in flexural strength. SRCB-2 and SRCB-2.5 exhibit reduced performance, particularly at early ages, which can be attributed to poor workability, fibre clustering, and inadequate dispersion that hinders uniform stress transfer across the matrix^{14,21,47,67,68}. These mixes still perform better than the control in the long term but are less efficient in converting fibre content into flexural gain.

**(a) Compressive strength testing****(b) Flexural strength testing****(c) Split tensile testing****(d) Broken Specimens 1****(e) Broken specimens 2****(f) Broken specimens 3****Fig. 2.** Sample images of fibrous GPC blends.

Split tensile strength

Figure 6 illustrates the split tensile strength development of geopolymer concrete mixes (SRCB0 to SRCB-2.5). The strength was measured at 7, 28, 90, and 180 days to assess both early-age and long-term tensile performance. The results indicate that tensile strength improves with age for all mixes due to progressive geopolymerization and matrix densification. The control mix (SRCB0) without basalt fibre shows a steady increase from around 3.0 MPa at 7 days to approximately 3.7 MPa at 180 days. With the inclusion of basalt fibre, a notable enhancement in split tensile strength is observed, particularly in mixes SRCB-0.5 and SRCB-1, which attain the highest values

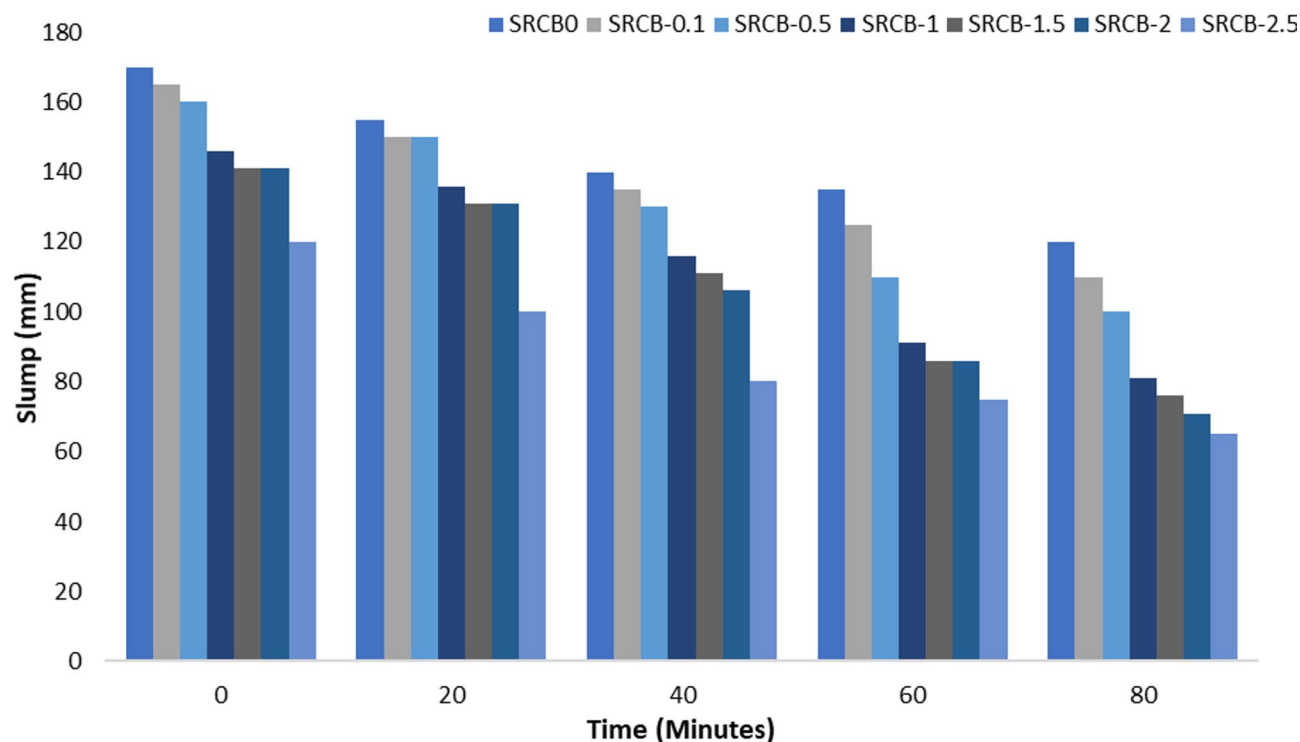


Fig. 3. Workability of fibrous GPC blends.

across all curing durations. SRCB-1, with 1% basalt fibre, reaches a peak tensile strength of approximately 4.8 MPa at 180 days, demonstrating the positive role of fibres in bridging microcracks and improving tensile stress distribution within the geopolymer matrix^{14,69–72}. However, mixes with higher fibre content, namely SRCB-1.5, SRCB-2, and SRCB-2.5, exhibit a gradual decline in strength. This decline becomes significant in SRCB-2.5, which records the lowest tensile strength across all ages, likely due to fibre balling, increased voids, and compromised compaction caused by excessive fibre volume^{68,72–74}.

Water absorption

Figure 7 illustrates the water absorption characteristics of various GPC mixes (SRCB0 to SRCB-2.5). The control mix (SRCB0), which contains no basalt fibres, shows a relatively high water absorption of approximately 8%, indicating a more porous microstructure. As basalt fibre is introduced, a progressive reduction in water absorption is observed, with SRCB-1 achieving the lowest value of around 5%. This can be attributed to the fibre's ability to enhance matrix densification, reduce pore connectivity, and bridge microvoids, thereby limiting the ingress of water^{14,58,75–77}. The mixes SRCB-0.1, SRCB-0.5, and SRCB-1 consistently demonstrate improved resistance to water absorption compared to the control, suggesting that fibre addition up to 1% enhances impermeability. However, beyond the optimal dosage, water absorption increases sharply. Mixes SRCB-1.5, SRCB-2, and especially SRCB-2.5 exhibit significantly higher absorption rates, with SRCB-2.5 exceeding even the control mix. This increase is likely due to poor workability, fibre agglomeration, and resulting voids caused by excessive fibre content, which create discontinuities in the matrix and compromise compaction quality^{71,73,76,78,79}.

Acid resistance

Figure 8 illustrates the weight loss (%) over 12 weeks for GPC mixes (SRCB0 to SRCB-1) exposed to an aggressive environmental condition (acidic medium). The mix (SRCB2.5), exhibits the highest weight loss, reaching nearly 38% by the 12th week. This significant deterioration reflects its lower resistance to chemical degradation due to its relatively porous matrix and balling of reinforcement. In contrast, the addition of basalt fibres significantly enhances the resistance to weight loss. SRCB-1, which contains 1% basalt fibre, demonstrates the lowest weight loss, stabilising around 6%, indicating superior structural integrity and chemical durability. Intermediate mixes like SRCB-0.1 and SRCB-0.5 show progressive improvements in performance, with weight losses ranging between 8 and 11% by the 12th week. These mixes reflect a transition from poor to enhanced durability as fibre content increases. The improved performance in fibre-reinforced mixes up to the optimum level is due to better matrix densification, crack-bridging ability of basalt fibres, and reduced ingress of aggressive agents through refined pore structures^{70,80–89}.

Rapid chloride ion penetration

Based on the RCPT values provided for the different geopolymer concrete mixes (SRCB0 to SRCB-2.5), the results clearly demonstrate the influence of basalt fibre dosage on the chloride ion penetrability and durability

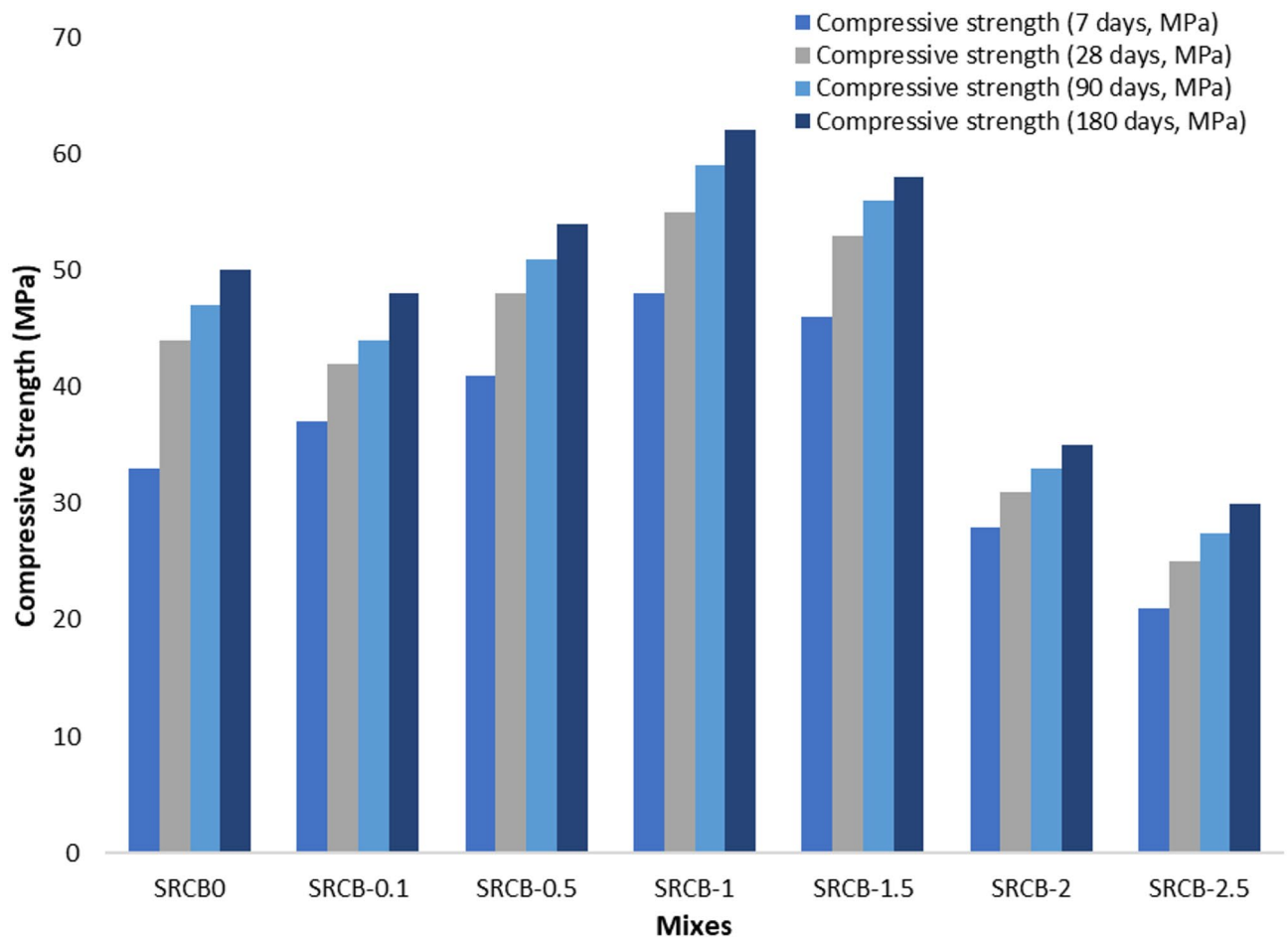


Fig. 4. Compressive strength of fibrous GPC blends.

performance of the composites. The control mix SRCB0, with no basalt fibre, exhibits a moderate chloride ion penetrability with an RCPT value of 3100 Coulombs, indicating a relatively porous structure vulnerable to chloride ingress. As basalt fibres are introduced, there is a noticeable improvement in resistance up to a certain threshold. Mixes SRCB-0.1, SRCB-0.5, and especially SRCB-1 show progressive enhancement in performance, with SRCB-1 achieving the lowest RCPT value of 1600 Coulombs, classified as low chloride ion penetrability. This improvement is attributed to the crack-bridging action of basalt fibres and matrix densification, which reduce permeability and enhance durability^{90–93}. However, as the basalt fibre content increases beyond 1%, performance begins to decline. While SRCB-1.5 still maintains a moderate to low penetrability rating at 2800 Coulombs, the mixes SRCB-2 and SRCB-2.5 register high chloride ion penetrability, with values of 4100 and 4300 Coulombs, respectively. These results align with the previously observed trends in water absorption and chemical resistance, suggesting that excessive fibre content leads to fibre agglomeration, reduced workability, and increased void formation, all of which contribute to higher permeability^{94–100}. Table 3 shows the RCPT results of the various mixes of fibrous GPC blends.

SEM analysis

Figure 9 shows the 180 days cured scanning electron microscopy (SEM) images of the basalt fibre-reinforced geopolymer concrete (GPC) mixes, each incorporating a ternary binder blend of SCBA (40%), RHA (30%), and CDA (30%) demonstrate how varying basalt fibre content (0.1–2.5%) influences the fibre–matrix interaction and overall microstructural integrity. The control mix (SRCB0) without basalt fibre shows a relatively porous microstructure with unrestrained matrix shrinkage cracks. The absence of fibre bridging leads to a less cohesive matrix, offering lower resistance to crack propagation and fluid ingress. No fibre–matrix interface is present, confirming the inferior mechanical and durability behaviour noted in test results^{14,20,22,100}. In SRCB0.1, the fibres appear well bonded with the matrix, and minimal surface debris or agglomeration is observed. However, due to the low fibre content, bridging networks are sparse, which limits the crack-arresting efficiency despite clean encapsulation. SRCB0.5 exhibits improved bonding density, with a noticeable increase in matrix adhesion and partial fibre coverage by reaction products, suggesting better interfacial development and mechanical interlock. The micrographs of SRCB1, the optimal mix, clearly show uniformly distributed basalt fibres embedded within a dense, compact geopolymer matrix. The fibres exhibit surface roughness with embedded gel particles, indicating both chemical bonding and physical interlock. No signs of debonding, micro-cracking, or fibre pull-out are

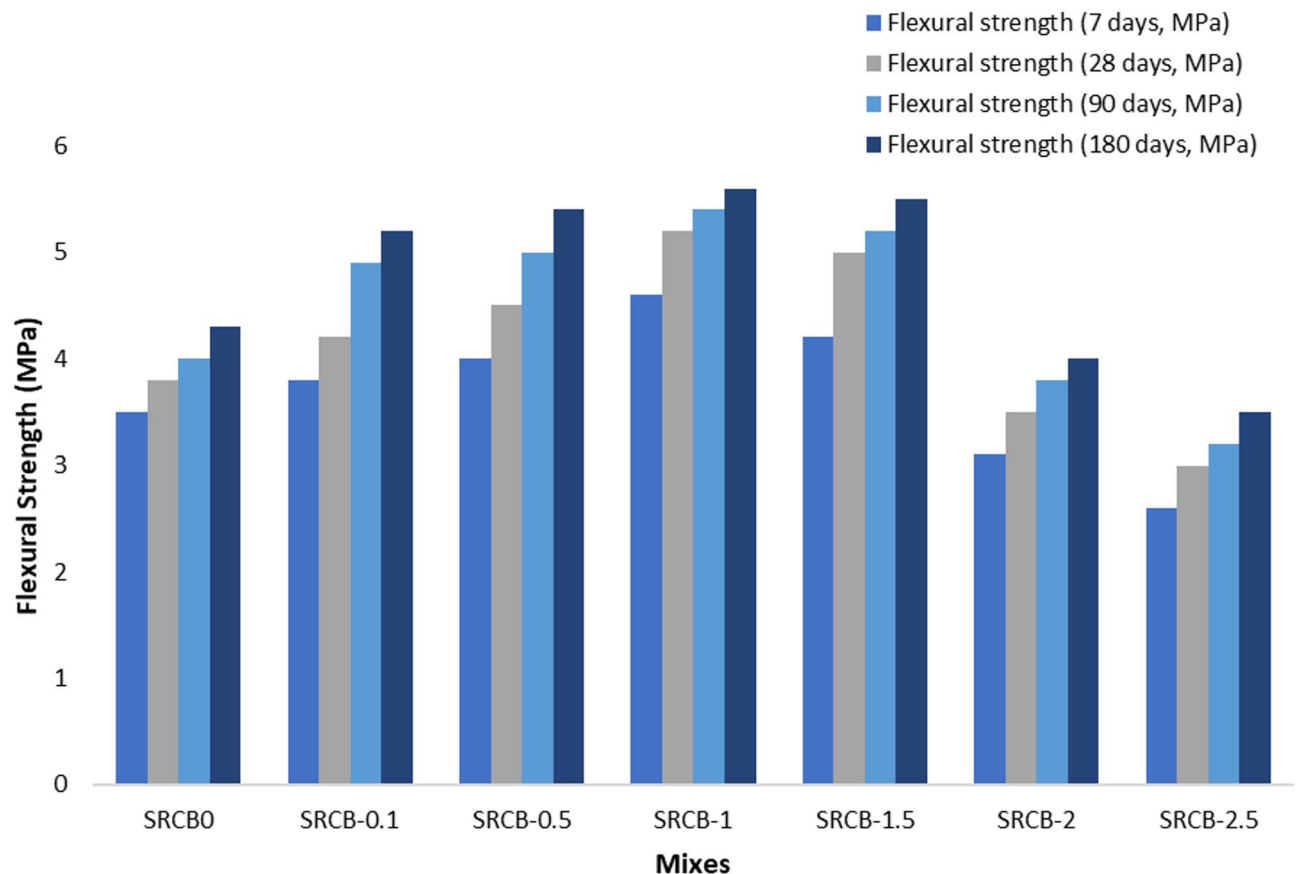


Fig. 5. Flexural strength of fibrous GPC blends.

visible, which directly supports the superior compressive, tensile, and durability performance observed for this mix^{46,47,101,102}. The matrix surrounding the fibres appears pore-free and continuous, reflecting optimal fibre dispersion and compatibility with the reactive gel phase. In SRCB1.5, although some level of matrix adhesion and encapsulation is still evident, early signs of fibre clustering begin to appear. There are occasional voids and regions where matrix contact appears incomplete, likely due to increased viscosity and reduced workability during casting. These defects may initiate microcracks under stress, contributing to the observed decline in performance beyond a 1% fibre content. The deterioration becomes more pronounced in SRCB2 and SRCB2.5, where fibre agglomeration is significant. SEM images show loosely packed bundles, entrapped air voids, and uneven bonding across the interface. Some fibres appear exposed, with insufficient matrix coverage, suggesting poor wetting and hindered geopolymer gel formation around the fibres^{21,59,70,103,104}. These flaws create weak zones, increasing porosity and permeability, which align with the observed rise in water absorption, chemical degradation, and RCPT values.

Regression analysis

Regression analysis was performed to establish quantitative relationships between the compressive strength of geopolymer concrete and its associated mechanical and durability properties, including flexural strength, split tensile strength, and water absorption. The square root of the 28-day compressive strength was used as the independent variable, in line with established correlations in geopolymer systems. Both linear and quadratic regression models were evaluated to assess the suitability of predictive relationships, with coefficients of determination (R^2) employed as indicators of goodness of fit. The analysis validates compressive strength as a key predictor of other performance parameters. By comparing results across multiple curing ages (7, 28, 90, and 180 days), the study highlights the progression of strength correlations over time and their implications for structural design and durability optimization of agro-waste-based geopolymer concrete.

Relationship between 7-day flexural strength and the square root of 28-day compressive strength

The regression analysis between the square root of 28-day compressive strength and the 7-day flexural strength demonstrates a strong correlation, with the linear regression model yielding a high coefficient of determination ($R^2 = 0.908$) as shown in Fig. 10. This indicates that more than 90% of the variability in flexural strength can be explained by the compressive strength of the mixes, establishing compressive strength as a reliable predictor of flexural performance. The observed data points closely follow the regression line, validating the accuracy of the model. Although both linear and quadratic trends were evaluated, the linear model provides a simpler and robust

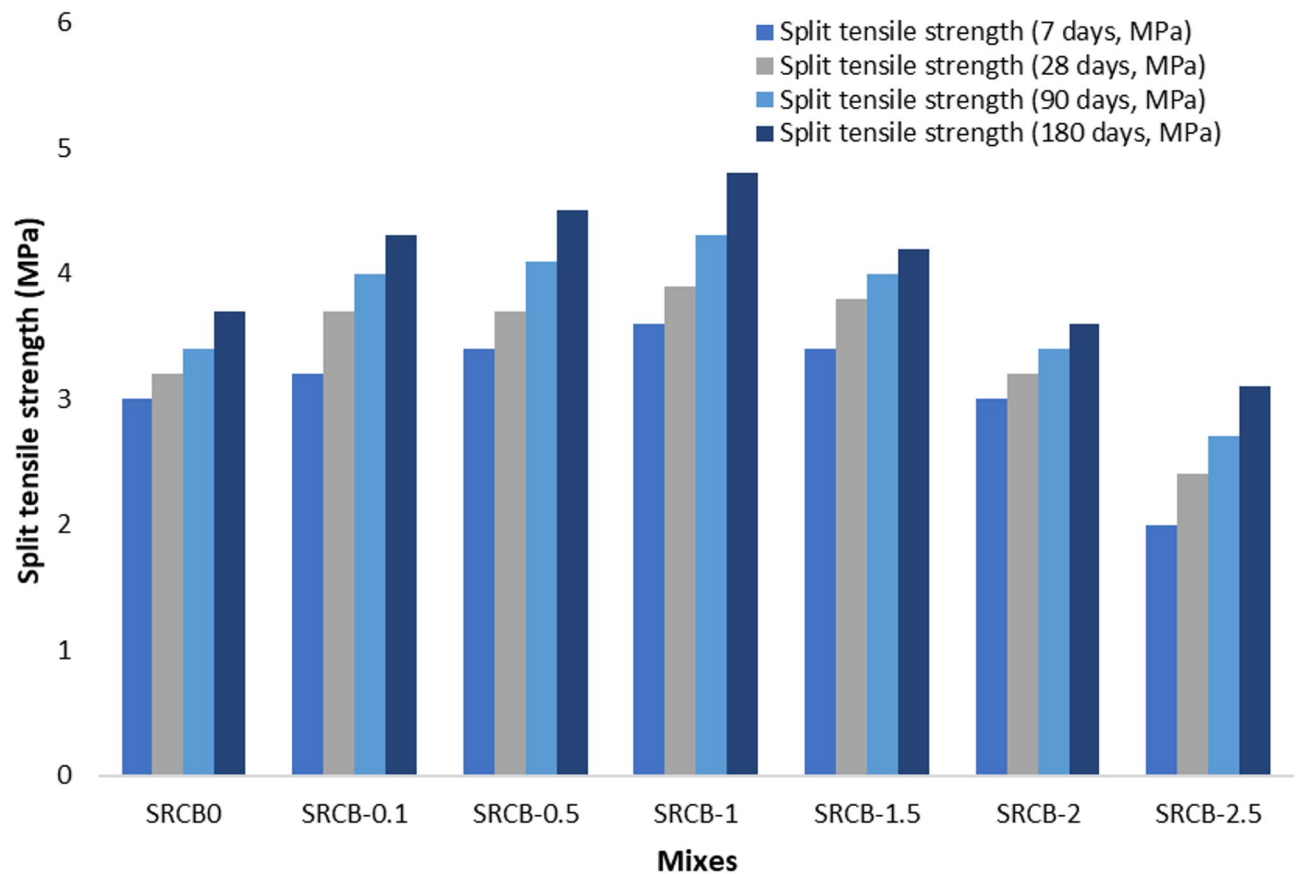


Fig. 6. Split tensile strength of fibrous GPC blends.

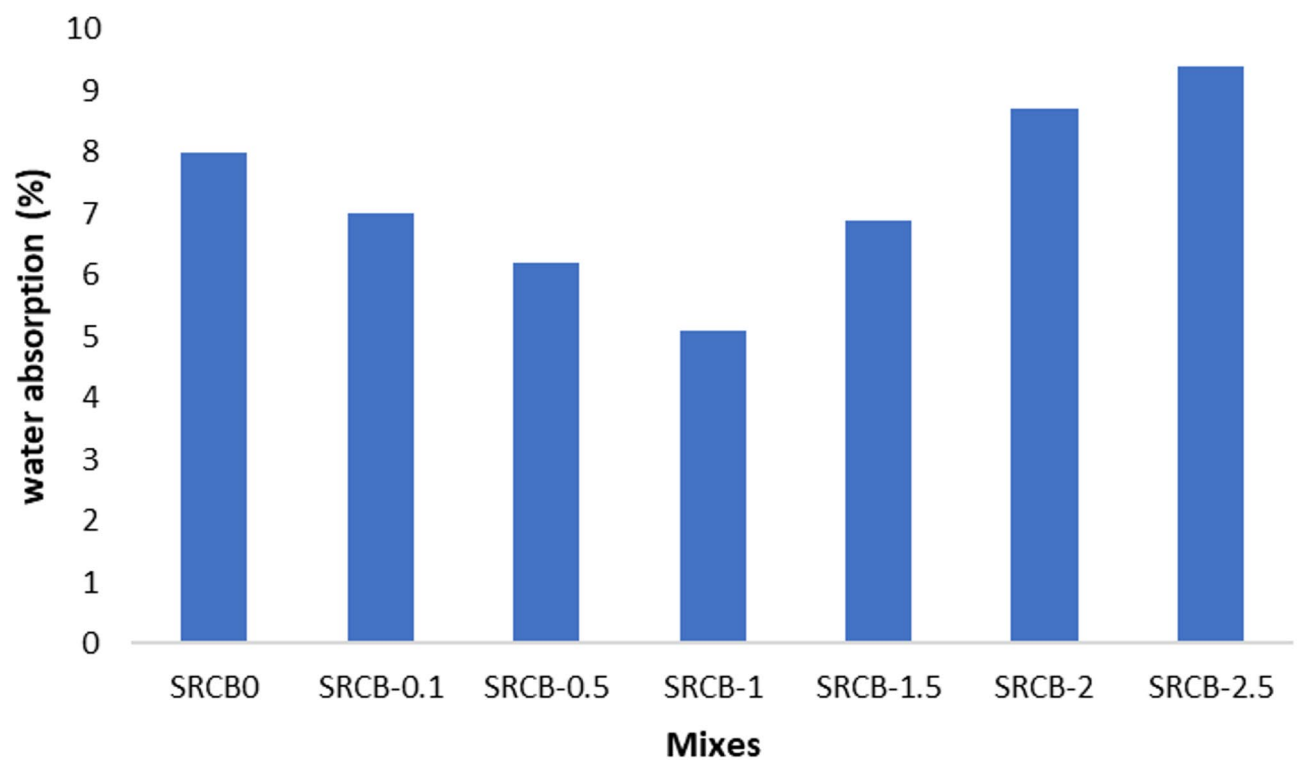


Fig. 7. Water absorption of fibrous GPC blends.

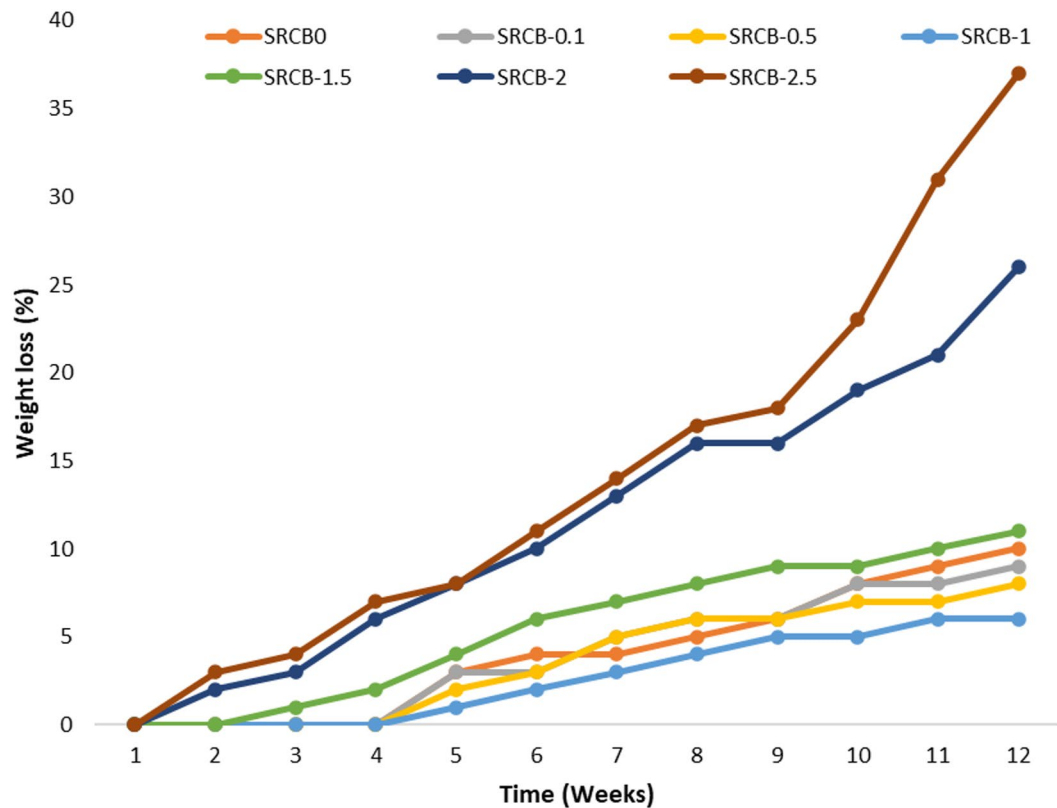


Fig. 8. Acid resistance of fibrous GPC blends.

Mix	RCPT value (Coulombs)	Chloride ion penetrability
SRCB0	3100	Moderate
SRCB-0.1	3000	Moderate
SRCB-0.5	2400	Moderate to low
SRCB-1	1600	Low
SRCB-1.5	2800	Moderate to low
SRCB-2	4100	High
SRCB-2.5	4300	High

Table 3. RCPT test of fibrous GPC blends.

fit, suitable for practical applications in predictive modeling of geopolymer concrete properties. The positive slope further reflects that an increase in compressive strength consistently enhances flexural strength, which is expected due to the improved matrix–fibre interaction and densification of the geopolymer microstructure. This correlation underscores the material’s suitability for structural applications where both compressive and flexural performance are critical. Equation 1 shows the relationship between the 7-day flexural strength of fibrous GPC specimens and the square root of 28-day compressive strength.

$$FS7 = 0.735\sqrt{CS28} - 1.073 \tag{1}$$

Relationship between 28-day flexural strength and the square root of 28-day compressive strength
The regression analysis between the square root of 28-day compressive strength and the 28-day flexural strength reveals a strong positive correlation, with the linear model achieving an R² value of 0.890 as shown in Fig. 11. This indicates that nearly 89% of the variation in flexural strength can be attributed to compressive strength, confirming the predictive reliability of compressive strength for flexural behavior in geopolymer concrete. The alignment of most data points with the regression line highlights the robustness of the linear fit, though slight deviations are observed at lower strength ranges. While the quadratic model attempts to capture minor non-linear trends, the linear regression remains sufficiently accurate and more practical for engineering applications. The results demonstrate that as compressive strength increases, flexural strength improves consistently due to enhanced geopolymer gel formation, better fibre–matrix bonding, and overall densification of the microstructure.

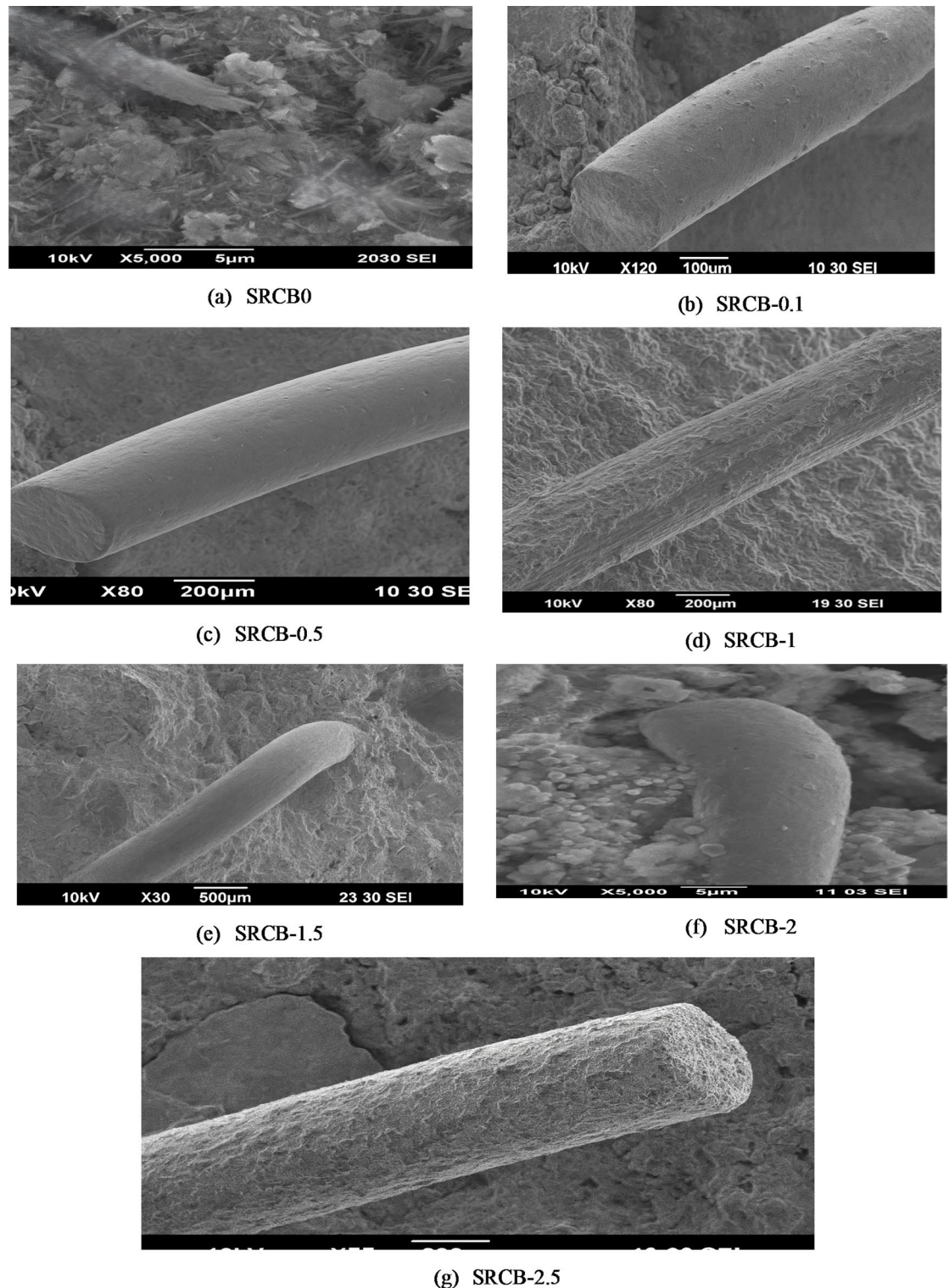


Fig. 9. SEM images of 180-day-cured fibrous GPC blends.

This strengthens the case for using compressive strength as a reliable indicator for flexural performance in mix design optimization. Equation 2 shows the relationship between the 28-day flexural strength of fibrous GPC specimens and the square root of 28-day compressive strength.

$$FS_{28} = 0.846\sqrt{CS_{28}} - 1.306 \quad (2)$$

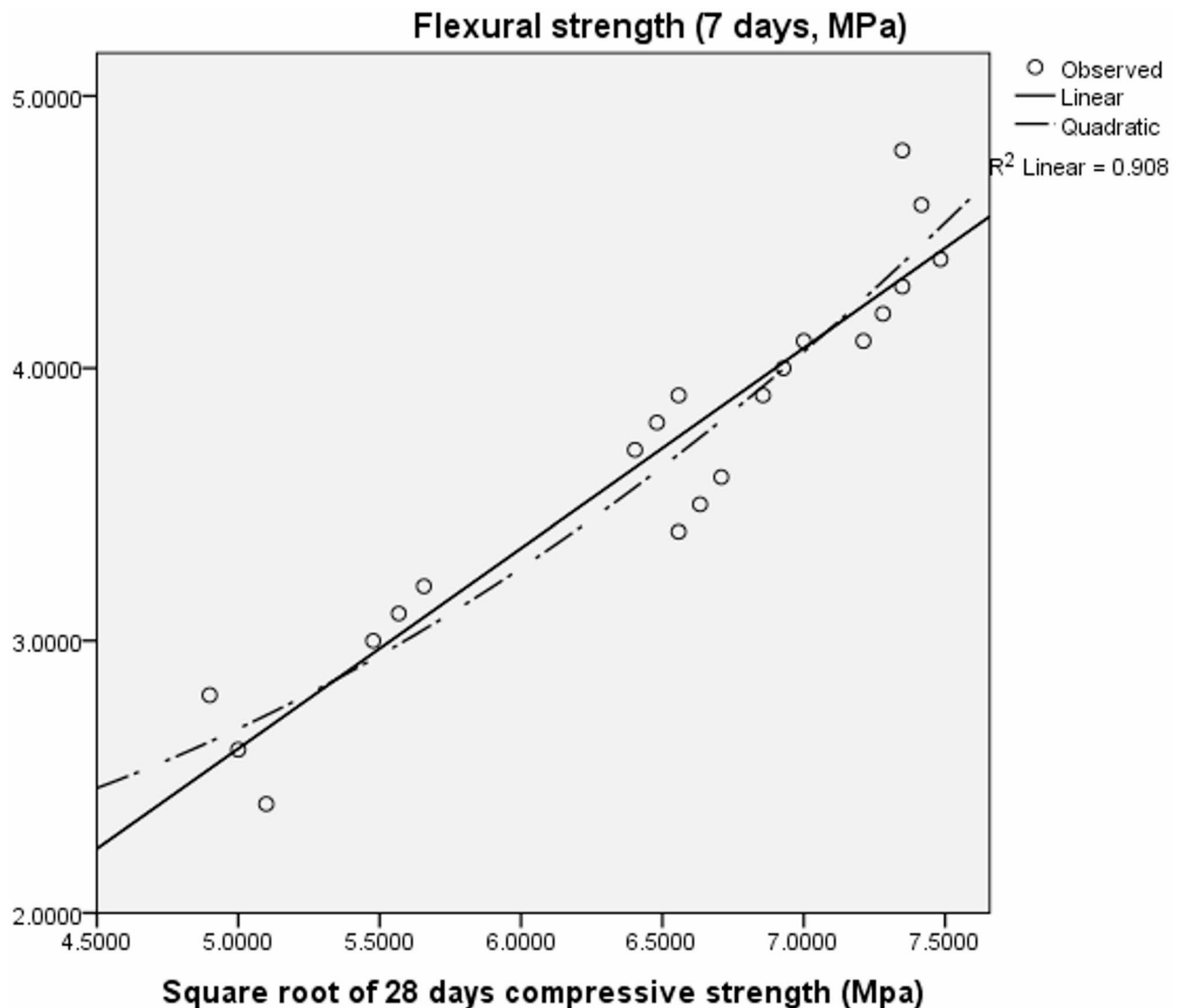


Fig. 10. Variation of 7-day flexural strength to the square root of 28-day compressive strength.

Relationship between 90-day flexural strength and the square root of 28-day compressive strength

The regression relationship between the square root of 28-day compressive strength and the 90-day flexural strength confirms a strong linear dependency, with an R^2 value of 0.852 as shown in Fig. 12. This indicates that approximately 85% of the variability in flexural strength is governed by compressive strength, reflecting a reliable predictive link even at extended curing periods. The clustering of data points along the regression line demonstrates good agreement, though minor deviations at higher strength levels suggest microstructural heterogeneity or fibre dispersion effects over time. The quadratic fit provides only marginal improvement compared to the linear model, reaffirming the sufficiency of linear regression for practical use. The positive correlation highlights that continued geopolymerization and fibre–matrix interactions enhance both compressive and flexural properties, even beyond standard curing durations. This result validates the long-term structural potential of agro-waste-based geopolymer concretes, establishing compressive strength as a dependable indicator of flexural performance at 90 days. Equation 3 shows the relationship between the 90-day flexural strength of fibrous GPC specimens and the square root of 28-day compressive strength.

$$FS_{90} = 0.874\sqrt{CS_{28}} - 1.168 \quad (3)$$

Relationship between 180-day flexural strength and the square root of 28-day compressive strength

The regression analysis between the square root of 28-day compressive strength and the 180-day flexural strength again confirms a strong linear correlation, with an R^2 value of 0.852 as shown in Fig. 13. This shows that about 85% of the variation in long-term flexural strength can be explained by compressive strength, validating compressive strength as a consistent predictor across extended curing durations. The regression line closely follows the observed data, with only minor scatter at higher strength levels, possibly due to micro-cracking, fibre

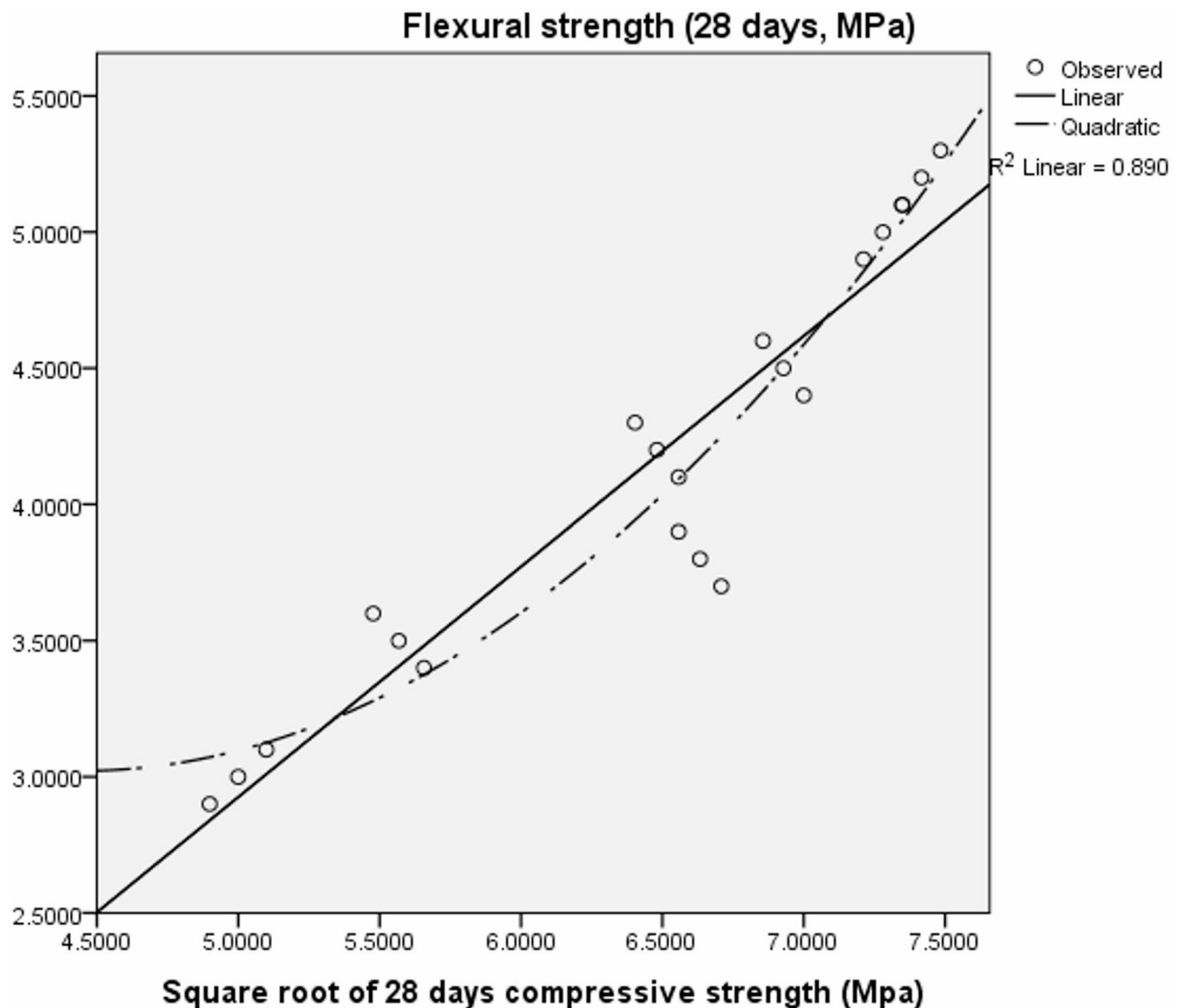


Fig. 11. Variation of 28-day flexural strength to the square root of 28-day compressive strength.

orientation, or long-term curing effects. Interestingly, the linear and quadratic models exhibit nearly identical fits, indicating that the relationship remains fundamentally linear even at 180 days. The findings suggest that as geopolymers continue to cure, both compressive and flexural strengths improve in tandem, reinforcing the durability and structural viability of agro-waste-based geopolymer systems over long service lives. Equation 4 shows the relationship between the 180-day flexural strength of fibrous GPC specimens and the square root of 28-day compressive strength.

$$FS_{180} = 0.872\sqrt{CS_{28}} - 0.857 \quad (4)$$

Relationship between 7-day split tensile strength and the square root of 28-day compressive strength

The regression relationship between the square root of 28-day compressive strength and the 7-day split tensile strength shows a moderate-to-strong correlation, with an R^2 value of 0.787 as shown in Fig. 14. This indicates that nearly 79% of the variability in tensile strength can be explained by compressive strength, establishing a reasonably strong predictive link even at early ages. The observed data points generally follow the regression line, though there is slightly higher scatter compared to flexural strength correlations, reflecting the inherent variability of tensile strength in geopolymer concrete. While the quadratic fit captures some of the curvature at lower strength ranges, the linear model remains sufficiently reliable for practical applications. The positive trend suggests that improvements in compressive strength translate into proportional gains in split tensile capacity, driven by enhanced matrix densification and improved fibre–binder bonding. However, the lower R^2 compared to flexural correlations highlights that tensile behavior is more sensitive to microstructural discontinuities and fibre distribution at early curing stages. Equation 5 shows the relationship between the 7-day tensile strength of fibrous GPC specimens and the square root of 28-day compressive strength.

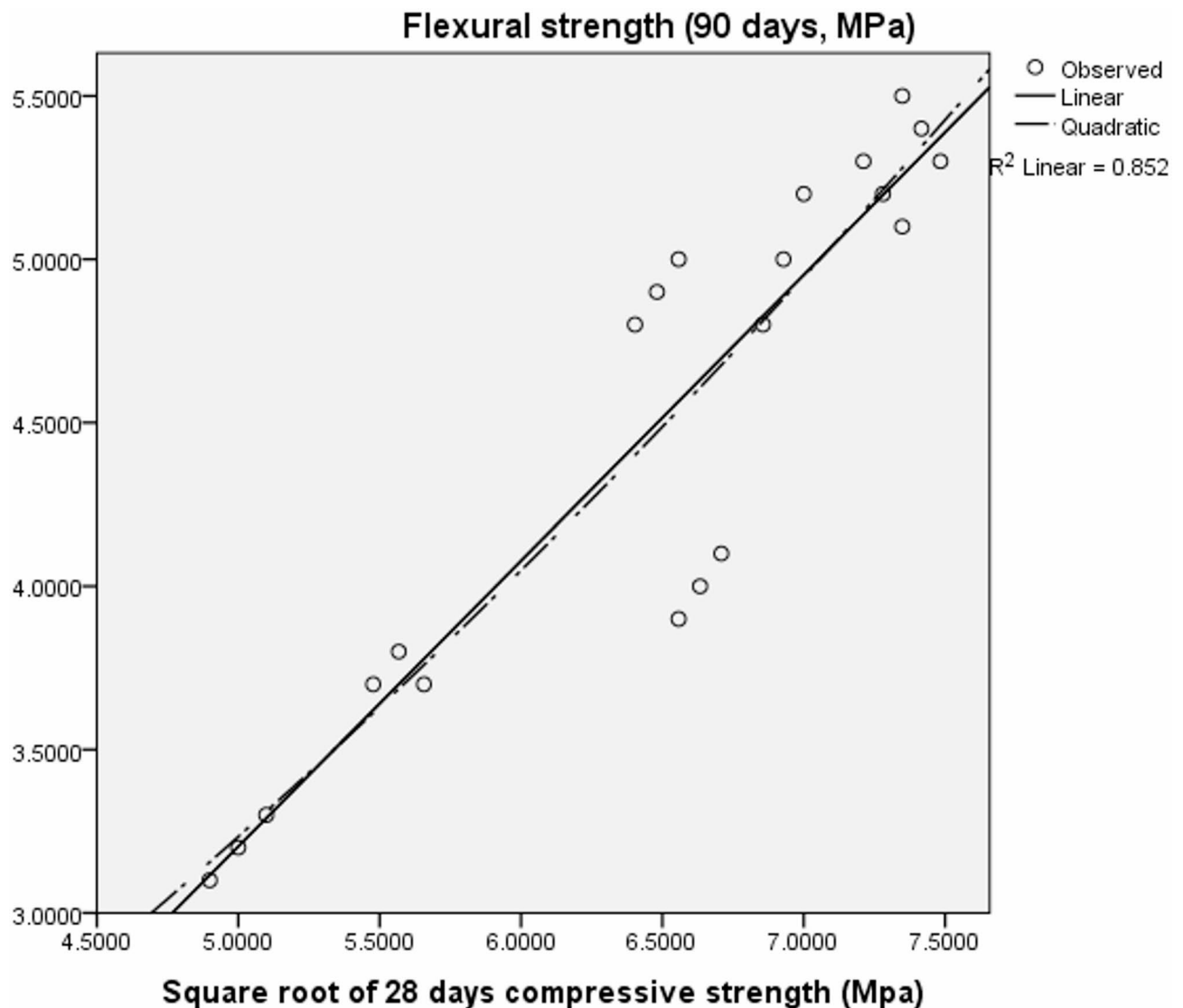


Fig. 12. Variation of 90-day flexural strength to the square root of 28-day compressive strength.

$$TS7 = 0.534\sqrt{CS28} - 0.368 \quad (5)$$

Relationship between 28-day split tensile strength and the square root of 28-day compressive strength

The regression analysis between the square root of 28-day compressive strength and the 28-day split tensile strength yields an R^2 value of 0.781, showing that approximately 78% of the variation in tensile strength can be explained by compressive strength. Similar to the 7-day trend, the data exhibits greater scatter compared to flexural strength regressions, reflecting the higher variability associated with tensile capacity in geopolymer concrete as shown in Fig. 15. The linear regression line provides a reasonably good fit, while the quadratic model captures minor deviations at lower compressive strength values. The positive relationship suggests that as compressive strength improves, tensile strength also increases consistently, driven by continued geopolymerization and matrix densification at 28 days. However, the slightly lower R^2 compared to flexural strength indicates that tensile behavior remains more sensitive to fibre distribution, microcracks, and interfacial bonding effects. Overall, compressive strength can be used as a predictor for split tensile performance, but with caution due to higher variability. Equation 6 shows the relationship between the 28-day tensile strength of fibrous GPC specimens and the square root of 28-day compressive strength

$$TS28 = 0.532\sqrt{CS28} - 0.26 \quad (6)$$

Relationship between 90-day split tensile strength and the square root of 28-day compressive strength

The regression analysis between the square root of 28-day compressive strength and the 90-day split tensile strength demonstrates a moderately strong correlation, with an R^2 value of 0.763 as shown in Fig. 16. This indicates that around 76% of the variation in tensile strength is explained by compressive strength, slightly

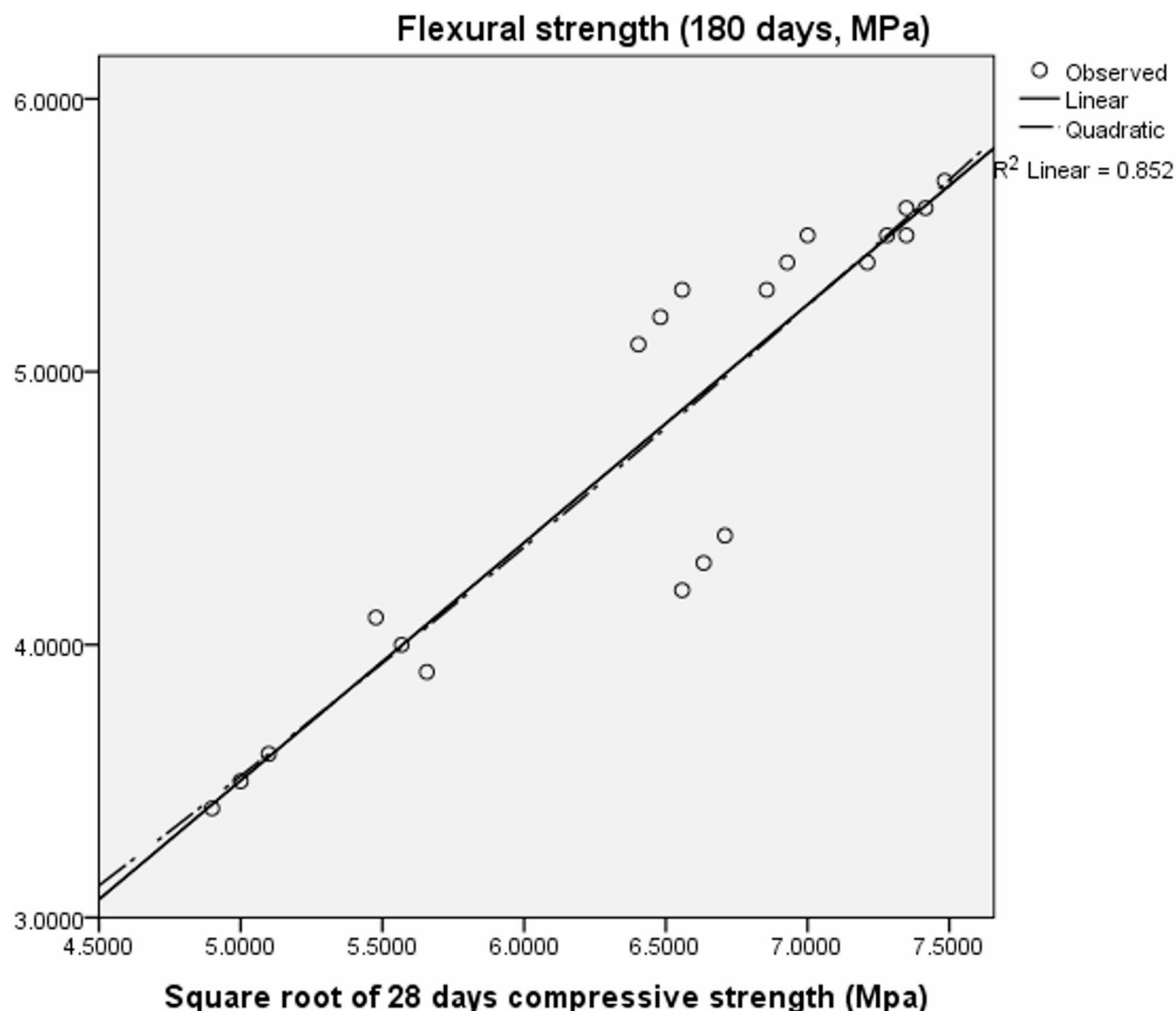


Fig. 13. Variation of 180-day flexural strength to the square root of 28-day compressive strength.

lower than the correlations observed for flexural strength. The data shows noticeable scatter, particularly at higher strength values, reflecting the sensitivity of tensile performance to factors such as fibre orientation, micro-cracks, and matrix heterogeneity that become more pronounced over longer curing periods. While both linear and quadratic fits align reasonably well with the observed data, the linear model provides a simpler and sufficiently accurate predictive relationship. The positive slope confirms that continuous improvements in compressive strength also enhance tensile capacity, although the predictive accuracy is somewhat weaker compared to flexural correlations. This highlights that while compressive strength can be used to estimate split tensile strength, variability must be accounted for in long-term performance predictions. Equation 7 shows the relationship between the 90-day tensile strength of fibrous GPC specimens and the square root of 28-day compressive strength

$$TS_{90} = 0.556\sqrt{CS_{28}} + 0.099 \quad (7)$$

Relationship between 180-day split tensile strength and the square root of 28-day compressive strength

The regression analysis between the square root of 28-day compressive strength and the 180-day split tensile strength indicates a consistent relationship, with an R^2 value of 0.765 as shown in Fig. 17. This suggests that around 77% of the variability in tensile strength can be predicted from compressive strength, which is comparable to the results observed at 90 days. The data distribution shows moderate scatter, particularly at higher compressive strength values, reflecting the inherent variability of tensile properties in geopolymer concretes. Both linear and quadratic models provide nearly identical fits, with the linear regression offering a simpler and more practical predictive approach. The positive slope confirms that tensile strength continues to increase in parallel with compressive strength over extended curing periods. However, the lower R^2 compared to

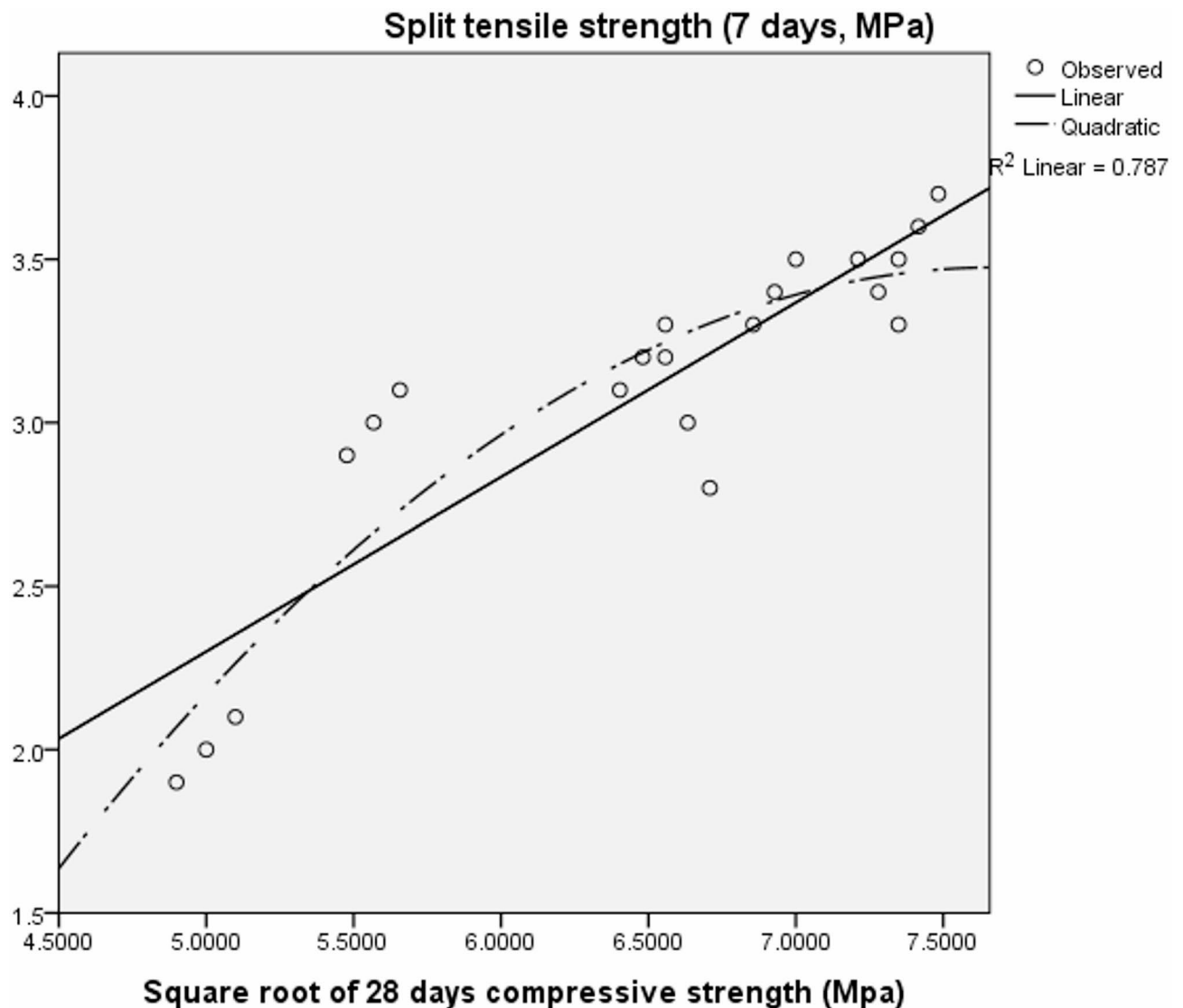


Fig. 14. Variation of 7-day tensile strength to the square root of 28-day compressive strength.

flexural strength correlations reinforces that tensile strength is more sensitive to microstructural heterogeneity and fibre orientation, even at long-term curing. These results validate compressive strength as a useful but not absolute predictor of tensile performance in geopolymer systems. Equation 8 shows the relationship between the 180-day tensile strength of fibrous GPC specimens and the square root of 28-day compressive strength

$$TS180 = 0.584\sqrt{CS28} + 0.246 \quad (8)$$

Relationship between 28-day water absorption and the square root of 28-day compressive strength

The regression analysis between the square root of 28-day compressive strength and water absorption (%) after 28 days of curing demonstrates a clear negative correlation, with an R² value of 0.751 as shown in Fig. 18. This indicates that about 75% of the variation in water absorption can be explained by compressive strength. The observed trend shows that as compressive strength increases, water absorption decreases significantly, highlighting the role of improved matrix densification and reduced pore connectivity in high-strength geopolymer concretes. The linear regression line captures this inverse relationship well, while the quadratic model only provides marginal adjustments at lower compressive strengths. The scatter in the data, particularly at mid-strength ranges, may be attributed to differences in fibre dispersion, curing uniformity, and microstructural heterogeneity. Overall, the results confirm that stronger mixes exhibit lower permeability and water absorption, which directly enhances durability and long-term performance. This establishes compressive strength not only as a predictor of mechanical performance but also as an indirect indicator of durability in geopolymer concrete systems. Equation 9 shows the relationship between the 28-day cured specimens' water absorption of fibrous GPC specimens and the square root of 28-day compressive strength. Table 4 shows the ANOVA results of the study.

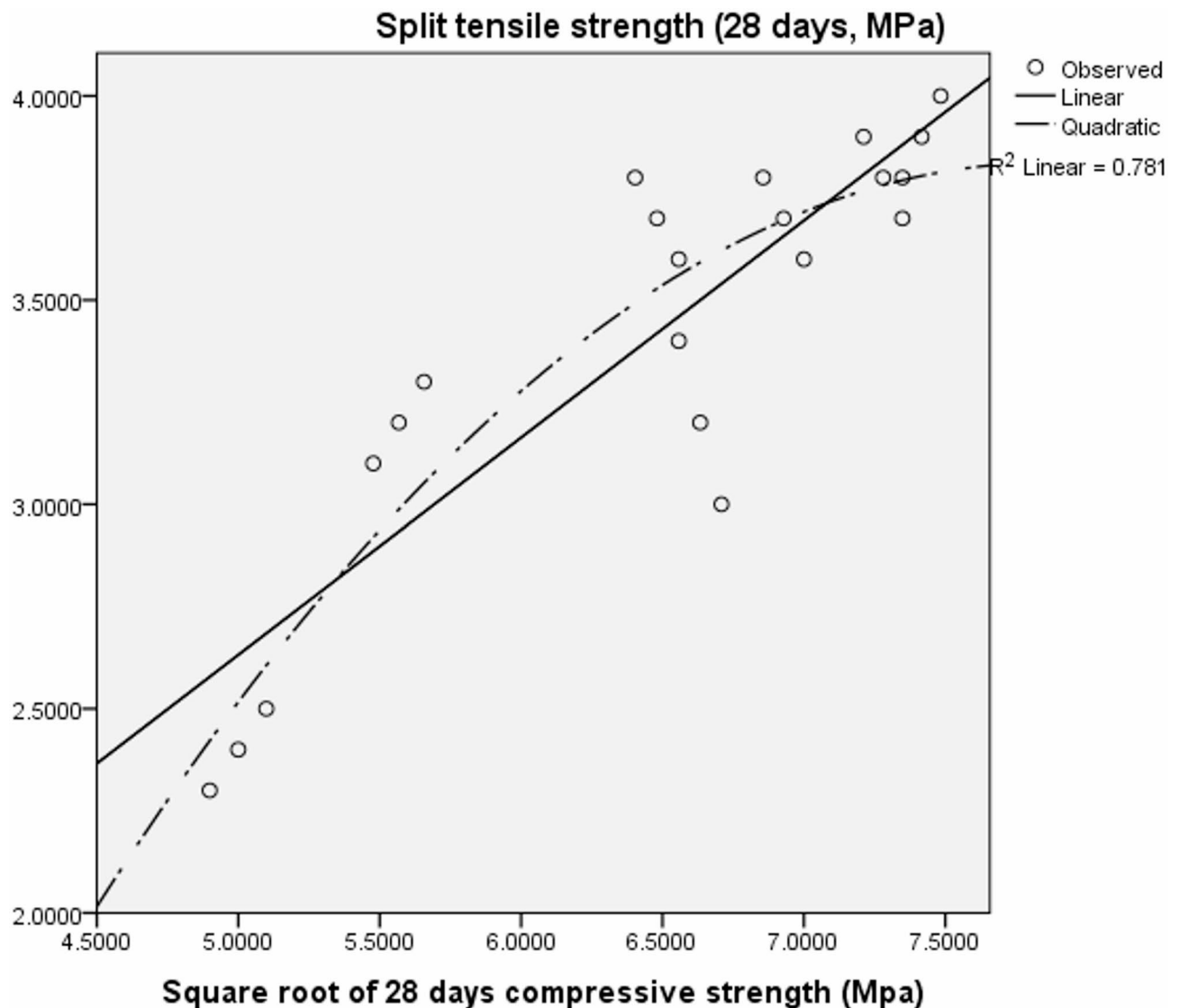


Fig. 15. Variation of 28-day tensile strength to the square root of 28-day compressive strength.

$$WA_{28} = -1.478\sqrt{CS_{28}} + 16.897 \quad (9)$$

The ANOVA results validate the significant role of basalt fibre dosage in governing both the mechanical and durability performance of geopolymer concrete. Across all responses, the quadratic term (Fibre²) recorded the highest percentage contribution (50–62%), confirming the parabolic behaviour of properties with fibre addition. This indicates that while modest increments in fibre content improve matrix densification and crack resistance, exceeding the optimum (1%) leads to fibre clustering, void formation, and loss of workability, ultimately reducing performance.

For compressive, flexural, and tensile strengths, the quadratic effect dominated (56–60%), while the linear effect explained 30–47%. Residual errors were consistently low (<10%), reflecting high statistical reliability. These outcomes show that fibres improve load transfer and crack bridging effectively up to 1% dosage, after which the adverse influence of poor dispersion outweighs the benefits.

The durability parameters (RCPT, water absorption, and acid resistance) exhibited similar nonlinear behaviour. Fibre² explained 50–62% of the variation, with RCPT and water absorption showing slightly higher residuals (20–24%) due to the intrinsic variability of durability tests. Acid resistance achieved the strongest statistical fit, with Fibre² contributing over 61%, highlighting that the optimum fibre level substantially improves resistance to chemical degradation.

Therefore, the ANOVA confirms that the quadratic effect is the dominant factor across all properties, consistently identifying 1% fibre as the optimum dosage. This statistical validation not only corroborates the experimental results but also underscores the robustness of the approach in predicting geopolymer concrete performance. The overall discussion insights of this study are provided in Table 5.

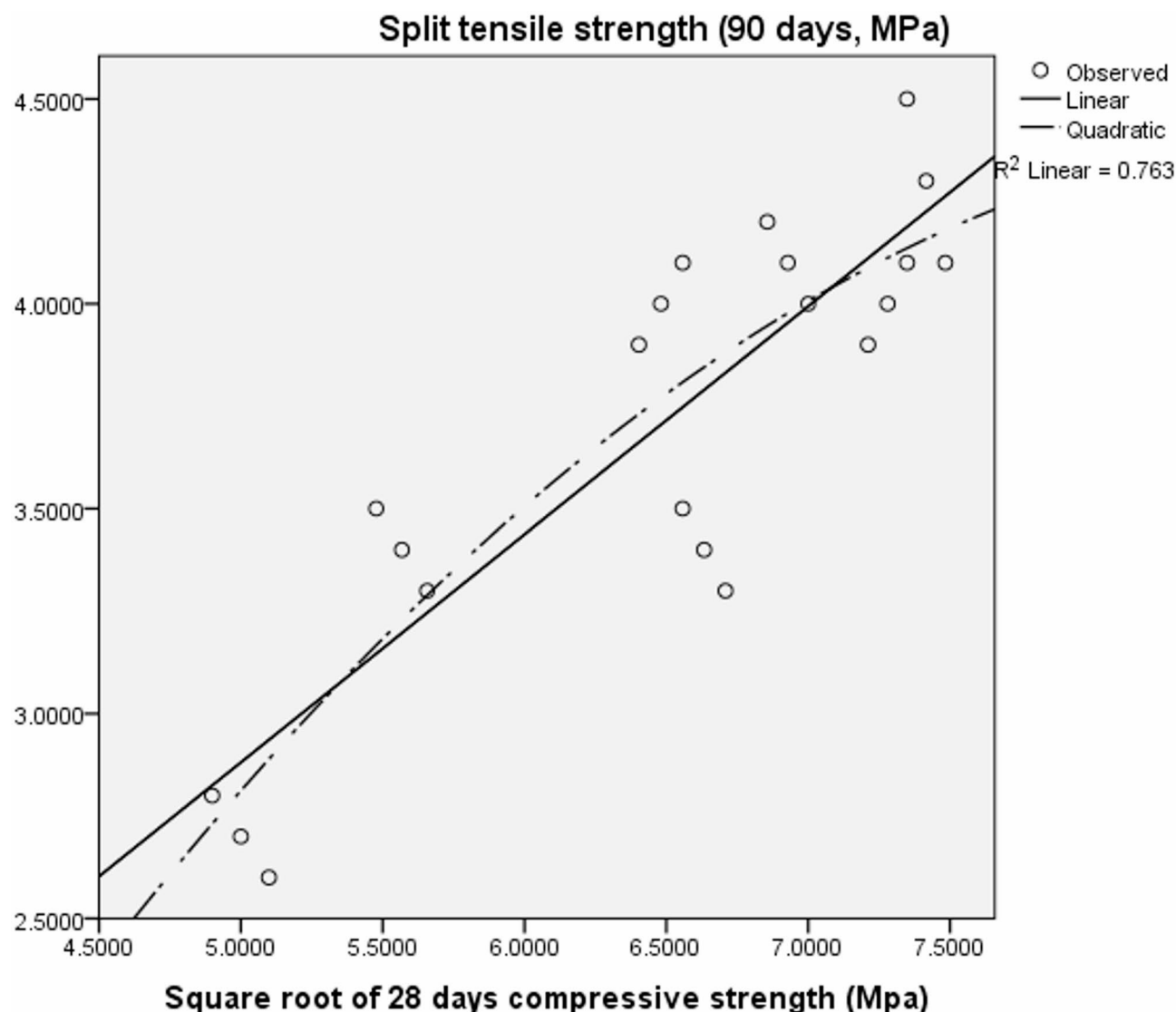


Fig. 16. Variation of 90-day tensile strength to the square root of 28-day compressive strength.

Conclusion

This study established the engineering and durability performance of agro-waste-based geopolymer concrete reinforced with basalt fibre. The following key conclusions can be drawn:

1. The incorporation of sugarcane bagasse ash, rice husk ash, and cow dung ash as binders provided a sustainable alternative to cement, enabling effective utilization of agro-residues.
2. Basalt fibre addition exhibited a parabolic influence on all measured properties, with an optimum dosage of 1%. At this level, compressive, flexural, and tensile strengths improved by up to 20 to 25% compared with the control, while RCPT values, water absorption, and acid loss were significantly reduced.
3. Higher fibre contents ($> 1.5\%$) led to clustering and voids, resulting in a decline in both mechanical strength and durability.
4. ANOVA analysis confirmed that the quadratic effect of fibre dosage dominated (50–62% contribution) across all responses, statistically validating the optimum performance at $\sim 1\%$ fibre.
5. The findings demonstrate that basalt fibre-reinforced agro-waste geopolymer concrete is a viable and eco-friendly construction material, combining mechanical efficiency, durability, and sustainability.

Future scope

The findings of this study open up several promising directions for future research and practical application. While the use of SCBA, RHA, and CDA in combination with basalt fibre has demonstrated significant improvements in mechanical and durability properties of geopolymer concrete, further investigations are essential to realise its full potential. Long-term durability studies under real-world exposure conditions, such as marine environments, freeze–thaw cycles, and carbonation, will help validate the performance of these

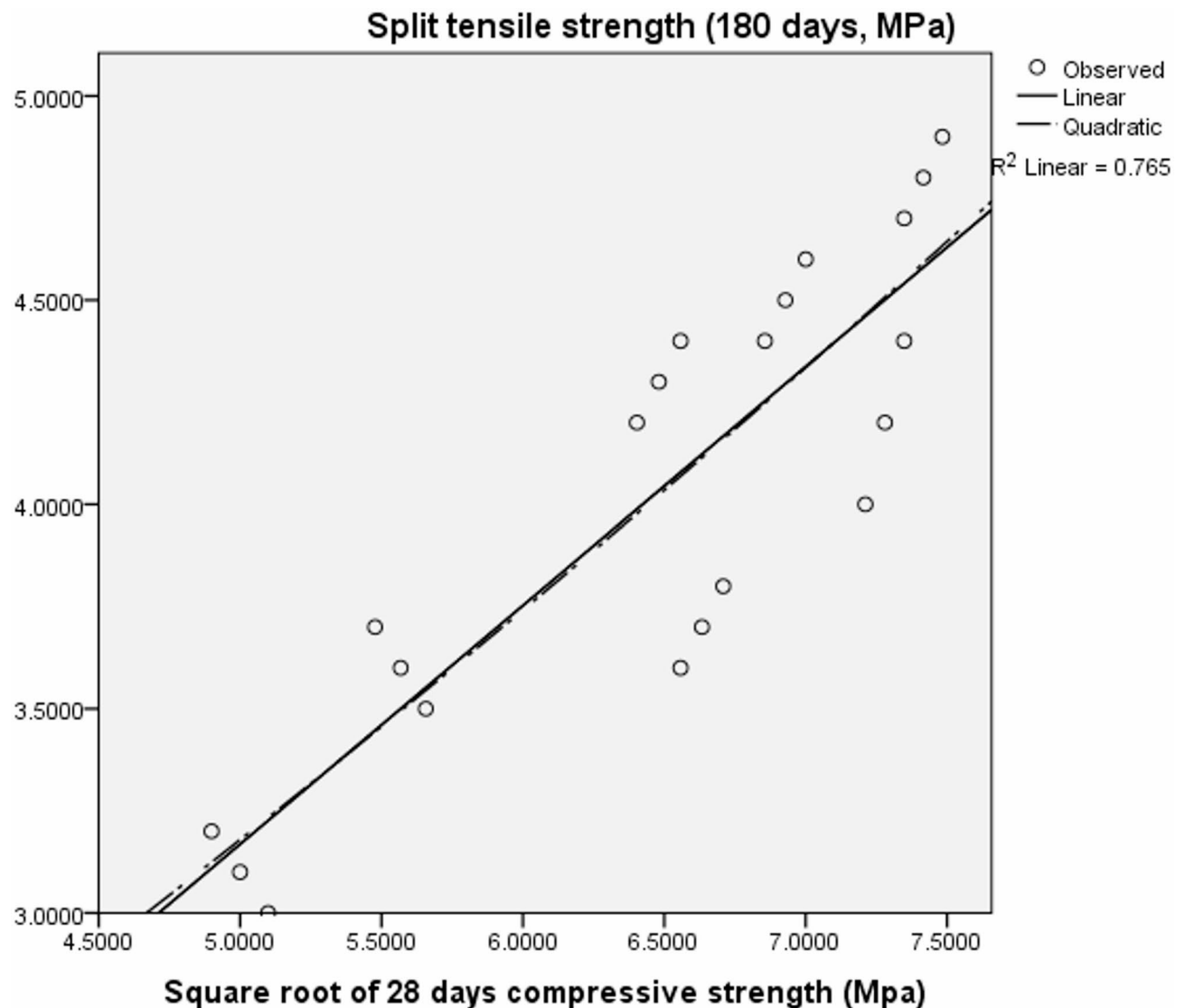


Fig. 17. Variation of 180-day tensile strength to the square root of 28-day compressive strength.

composites in diverse climatic regions. Additionally, microstructural analysis using techniques like SEM, XRD, and CT scanning can provide a deeper understanding of fibre-matrix interactions, pore structure refinement, and crack propagation resistance. Exploring hybrid fibre systems and the integration of machine learning for mix optimization could further enhance the strength and functional properties of the material. The potential use of these sustainable mixes in 3D printing applications also offers an innovative path toward rapid, low-carbon construction technologies. Field-scale trials and structural performance evaluations will be crucial for assessing constructability and scalability. Moreover, life cycle assessment (LCA) and carbon footprint analysis should be undertaken to quantify the environmental benefits over conventional cement concrete. Finally, the development of dedicated technical standards and codal provisions for fibre-reinforced geopolymer concrete made with agro-waste will play a key role in facilitating its adoption in mainstream construction.

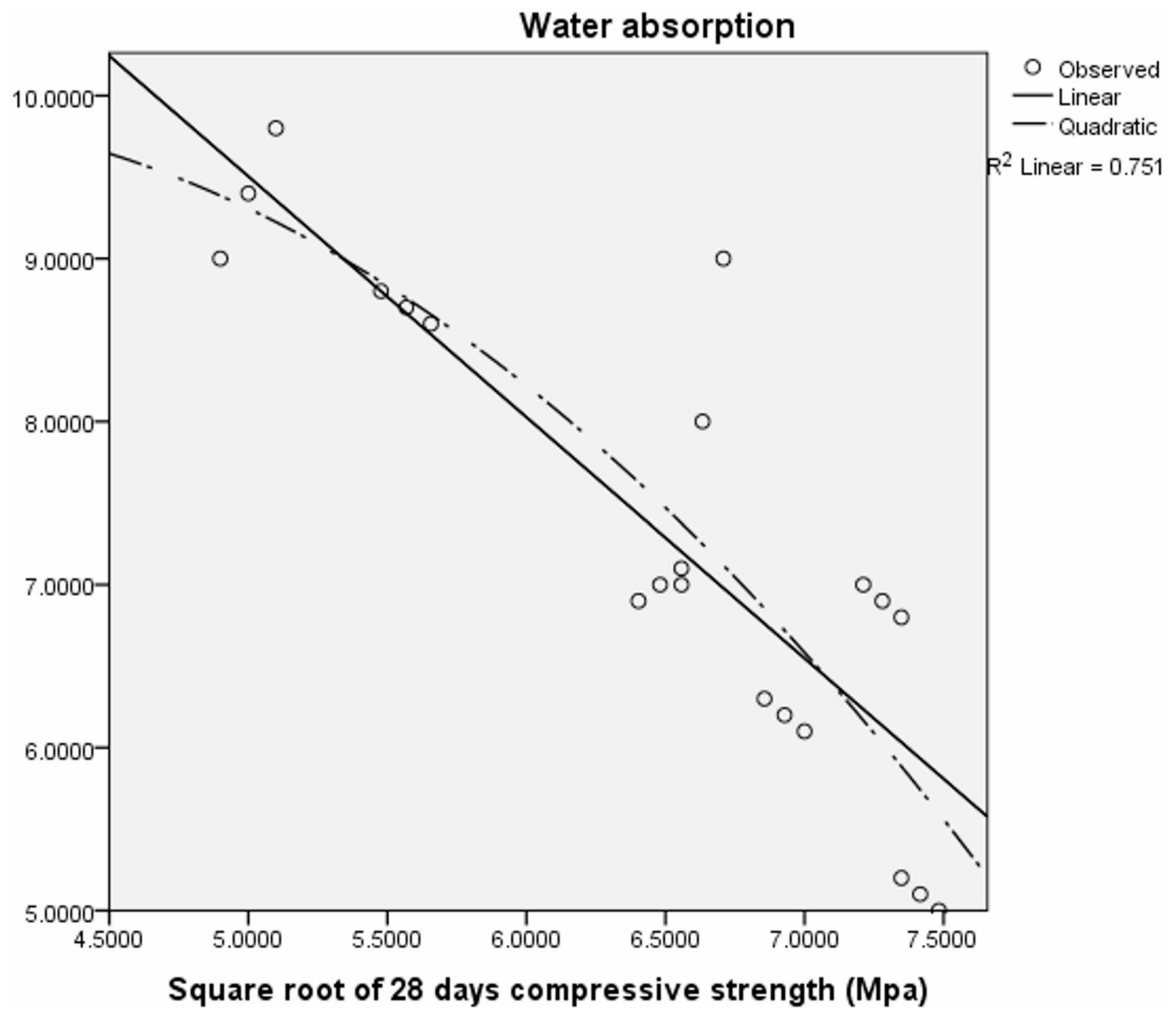


Fig. 18. Variation of water absorption (%) to the square root of 28-day compressive strength.

Response	Source	SS	Adj SS	DF	F Value	p-value	% Contribution
Compressive strength (MPa)	Fibre	122.758	122.758	1	18.49	0.013	32.94
	Fibre ²	223.374	223.374	1	33.64	0.004	59.94
	Residual	26.561	26.561	4	–	–	7.13
Flexural strength (MPa)	Fibre	1.543	1.543	1	44.80	0.003	46.99
	Fibre ²	1.603	1.603	1	46.54	0.002	48.82
	Residual	0.138	0.138	4	–	–	4.20
Split tensile strength (MPa)	Fibre	0.899	0.899	1	17.83	0.013	36.00
	Fibre ²	1.397	1.397	1	27.69	0.006	55.92
	Residual	0.202	0.202	4	–	–	8.08
RCPT (Coulombs)	Fibre	1,225,486	1,225,486	1	4.30	0.107	26.02
	Fibre ²	2,344,871	2,344,871	1	8.23	0.046	49.78
	Residual	1,140,277	1,140,277	4	–	–	24.21
Water absorption (%)	Fibre	4.428	4.428	1	6.53	0.063	32.83
	Fibre ²	6.346	6.346	1	9.36	0.038	47.06
	Residual	2.711	2.711	4	–	–	20.11
Acid loss (%)	Fibre	203.050	203.050	1	23.92	0.008	32.84
	Fibre ²	381.216	381.216	1	44.90	0.003	61.66
	Residual	33.958	33.958	4	–	–	5.49

Table 4. ANOVA results.

Property	Observed trend across fibre dosage	Discussion insights
Workability	Workability decreases as fibre content increases, with a steep reduction beyond 1.5%	Increased internal friction and fibre interlocking reduce flowability. Similar behaviour reported in fibre-reinforced GPC systems ^{14,20,47}
Compressive strength	Strength increases from 0 to 1% fibre content, then declines at ≥ 1.5%	Basalt fibres enhance crack-bridging and load transfer at low dosages; excessive fibres cause clustering and voids, reducing strength ^{37–59}
Flexural strength	Rises significantly up to 1%, slightly drops at 1.5%, declines sharply at 2–2.5%	Optimum fibre dispersion at 1% improves energy absorption and post-crack behaviour; high fibre content reduces stress transfer efficiency ^{63,64,67}
Split tensile strength	Parabolic trend: peak at 1%, reduction thereafter	Tensile strength is highly sensitive to fibre orientation and matrix bonding; over-reinforcement causes weak zones and fibre pull-out ^{69–71}
Water absorption	Drops from control to 1% (dense microstructure), rises significantly above 1.5%	Fibre densification reduces pore connectivity; void formation and agglomeration at higher dosages increase permeability ^{72,73,76}
Acid resistance	Lowest deterioration (6%) at 1% fibre; severe degradation (38%) at 2.5%	Improved integrity of optimally reinforced matrix resists sulphuric acid; poor matrix cohesion in high-fibre mixes accelerates leaching and mass loss ^{70,84,88}
RCPT	Low for 1% fibre (1600 C), increases sharply for 2–2.5% mixes (4100–4300 C)	Enhanced matrix sealing at optimal fibre content; fibre balls increase chloride pathways when dosage exceeds 1% ^{71,90,94}
Microstructure	SRCB1 shows dense gel matrix and strong fibre bonding; SRCB2–2.5 show agglomeration, voids, and weak interfaces	Microstructure correlates directly with mechanical and durability trends; uniform distribution is critical for performance ^{20,46,101}
ANOVA statistical behaviour	Fibre ² term contributes 50–62% across all responses; residual error < 10%	Confirms that the behaviour is parabolic with an optimum at 1%; excessive fibre content consistently deteriorates performance [ANOVA Table]
Overall behaviour	Optimum performance consistently at 1% basalt fibre	Reinforcement improves matrix behaviour only within a narrow dosage window, aligning with literature recommendations for GPC fibre systems ^{14,45,60}

Table 5. Overall discussion of the study.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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References

1. Amran, Y. H. M., Alyousef, R., Alabduljabbar, H. & El-Zeadani, M. Clean production and properties of geopolymer concrete; A review. *J. Clean. Prod.* <https://doi.org/10.1016/J.JCLEPRO.2019.119679> (2020).
2. Amran, M. et al. Long-term durability properties of geopolymer concrete: An in-depth review. *Case Stud. Constr. Mater.* <https://doi.org/10.1016/J.CSCM.2021.E00661> (2021).
3. Gartner, E. Industrially interesting approaches to ‘low-CO₂’ cements. *Cem. Concr. Res.* **34**(9), 1489–1498. <https://doi.org/10.1016/j.cemconres.2004.01.021> (2004).
4. Kanagaraj, B., Anand, N., Johnson Alengaram, U., Samuvel Raj, R. & Lubloy, E. A comprehensive review on life-cycle assessment of concrete using industrial by-products. *Case Stud. Chem. Environ. Eng.* **12**, 101260. <https://doi.org/10.1016/j.cscee.2025.101260> (2025).

5. Davidovits, J. & France, S. Synthesis of new high-temperature geo-polymers for reinforced plastics/composites, no. January 1979 (2018).
6. Zhu, H., Zhang, Z., Zhu, Y. & Tian, L. Durability of alkali-activated fly ash concrete: Chloride penetration in pastes and mortars. *Constr. Build. Mater.* **65**, 51–59. <https://doi.org/10.1016/j.conbuildmat.2014.04.110> (2014).
7. Luukkonen, T., Abdollahnejad, Z., Yliniemi, J., Kinnunen, P. & Illikainen, M. One-part alkali-activated materials: A review. *Cem. Concr. Res.* **103**, 21–34. <https://doi.org/10.1016/j.cemconres.2017.10.001> (2018).
8. Junaid, M. T., Kayali, O., Khennane, A. & Black, J. A mix design procedure for low calcium alkali activated fly ash-based concretes. *Constr. Build. Mater.* **79**, 301–310. <https://doi.org/10.1016/j.conbuildmat.2015.01.048> (2015).
9. Kanagaraj, B., Anand, N., Raj, S. & Lubloy, E. Behavioural studies on binary blended high strength self compacting geopolymer concrete exposed to standard fire temperature. *Ain Shams Eng. J.* <https://doi.org/10.1016/j.asej.2023.102394> (2024).
10. Kanagaraj, B., Anand, N., Andrushia, A. D. & Lubloy, E. Investigation on engineering properties and micro-structure characteristics of low strength and high strength geopolymer composites subjected to standard temperature exposure. *Case Stud. Constr. Mater.* <https://doi.org/10.1016/j.cscm.2022.e01608> (2022).
11. Kumaravel, S. & Sivakumar, I. Influence of fibre reinforced geopolymer concrete. *Int. J. Res. Anal. Rev. (IJRAR)* **5**(4), 111–114 (2018).
12. Mahmoodi, O., Siad, H., Lachemi, M., Dadsetan, S. & Sahmaran, M. Development and characterization of binary recycled ceramic tile and brick wastes-based geopolymers at ambient and high temperatures. *Constr. Build. Mater.* <https://doi.org/10.1016/j.conbuildmat.2021.124138> (2021).
13. Nath, P. & Sarker, P. K. Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition. *Constr. Build. Mater.* **66**, 163–171. <https://doi.org/10.1016/j.conbuildmat.2014.05.080> (2014).
14. Abbass, M. & Singh, G. Experimental investigation of alkali-activated hybrid geopolymer concrete. *Multiscale Multidiscip. Model. Exp. Des.* **6**(2), 235–249. <https://doi.org/10.1007/s41939-023-00144-1> (2023).
15. Abbass, M., Singh, D. & Singh, G. Properties of hybrid geopolymer concrete prepared using rice husk ash, fly ash and GGBS with coconut fiber. *Mater. Today Proc.* **45**, 4964–4970. <https://doi.org/10.1016/j.matpr.2021.01.390> (2021).
16. Verma, M. & Dev, N. Effect of ground granulated blast furnace slag and fly ash ratio and the curing conditions on the mechanical properties of geopolymer concrete. *Struct. Concr.* **23**(4), 2015–2029. <https://doi.org/10.1002/suco.202000536> (2022).
17. Verma, M. & Dev, N. Effect of SNF-based superplasticizer on physical, mechanical and thermal properties of the geopolymer concrete. *SILICON* **14**(3), 965–975. <https://doi.org/10.1007/s12633-020-00840-4> (2022).
18. Kanagaraj, B., Anand, N., Samuvel Raj, R. & Lubloy, E. Performance evaluation on engineering properties of sodium silicate binder as a precursor material for the development of cement-free concrete. *Dev. Built Environ.* <https://doi.org/10.1016/j.dibe.2022.100092> (2022).
19. Kanagaraj, B., Kiran, T., Al Jabri, K. & Justin, S. Development and strength assessment of eco-friendly geopolymer concrete made with natural and recycled aggregates. *Constr. Innov.* **23**(3), 524–545. <https://doi.org/10.1108/CI-08-2021-0157> (2023).
20. Abbass, M. & Singh, G. Microstructural analysis of environment friendly sustainable geopolymer concrete. *Multiscale Multidiscip. Model. Exp. Des.* **7**(1), 301–319. <https://doi.org/10.1007/s41939-023-00200-w> (2024).
21. Subramanian, N., Solaiyan, E., Sendrayaperumal, A. & Lakshmaiya, N. Flexural behaviour of geopolymer concrete beams reinforced with BFRP and GFRP polymer composites. *Adv. Struct. Eng.* **25**(5), 954–965. <https://doi.org/10.1177/13694332211054229> (2022).
22. Trabacchin, G., Sebastian, W. & Zhang, M. Experimental and analytical study of bond between basalt FRP bars and geopolymer concrete. *Constr. Build. Mater.* <https://doi.org/10.1016/j.conbuildmat.2021.125461> (2022).
23. Bagheri, A. et al. Microstructural study of environmentally friendly boroaluminosilicate geopolymers. *J. Clean. Prod.* **189**, 805–812. <https://doi.org/10.1016/j.jclepro.2018.04.034> (2018).
24. Nath, P. & Sarker, P. K. Flexural strength and elastic modulus of ambient-cured blended low-calcium fly ash geopolymer concrete. *Constr. Build. Mater.* **130**, 22–31. <https://doi.org/10.1016/j.conbuildmat.2016.11.034> (2017).
25. Kiran, K. et al. High-temperature performance of ambient-cured alkali-activated binder concrete. *Innov. Infrastruct. Solut.* **6**(2), 1–11. <https://doi.org/10.1007/s41062-020-00448-y> (2021).
26. Zaetang, Y., Wongsu, A., Sata, V. & Chindaprasit, P. Use of coal ash as geopolymer binder and coarse aggregate in pervious concrete. *Constr. Build. Mater.* **96**, 289–295. <https://doi.org/10.1016/j.conbuildmat.2015.08.076> (2015).
27. Kanagaraj, B., Anand, N., Samuvel Raj, R. & Lubloy, E. Techno-socio-economic aspects of portland cement, geopolymer, and limestone calcined clay cement (LC3) composite systems: A-state-of-art-review. *Constr. Build. Mater.* **398**, 132484. <https://doi.org/10.1016/j.conbuildmat.2023.132484> (2023).
28. Kanagaraj, B., Lubloy, E., Anand, N., Hlavicka, V. & Kiran, T. Investigation of physical, chemical, mechanical, and microstructural properties of cement-less concrete—State-of-the-art review. *Constr. Build. Mater.* **365**, 130020. <https://doi.org/10.1016/j.conbuildmat.2022.130020> (2023).
29. Chindaprasit, P., Chareerat, T. & Sirivivatnanon, V. Workability and strength of coarse high calcium fly ash geopolymer. *Cem. Concr. Compos.* **29**(3), 224–229. <https://doi.org/10.1016/j.cemconcomp.2006.11.002> (2007).
30. Ghafoor, M. T., Khan, Q. S., Qazi, A. U., Sheikh, M. N. & Hadi, M. N. S. Influence of alkaline activators on the mechanical properties of fly ash based geopolymer concrete cured at ambient temperature. *Constr. Build. Mater.* <https://doi.org/10.1016/j.conbuildmat.2020.121752> (2021).
31. Oyeibisi, S., Ede, A., Olutoge, F., Ofuyatan, O. & Alayande, T. Influence of alkali concentrations on the mechanical properties of geopolymer concrete. *Int. J. Civ. Eng. Technol.* **9**(8), 734–743 (2018).
32. Gómez-Casero, M. A., Pérez-Villarejo, L., Castro, E. & Eliche-Quesada, D. Reinforcement of alkali-activated cements based matrices using olive pruning fibres as an alternative to traditional fibres. *Sustain. Chem. Pharm.* <https://doi.org/10.1016/j.scp.2024.101433> (2024).
33. Cai, J., Li, X., Tan, J. & Vandevyvere, B. Thermal and compressive behaviors of fly ash and metakaolin-based geopolymer. *J. Build. Eng.* <https://doi.org/10.1016/j.jobbe.2020.101307> (2020).
34. Abbass, M. & Singh, G. Fatigue analysis of rice husk ash and basalt fibre-based sustainable geopolymer concrete in rigid pavements. *Mater. Today Proc.* **45**, 5014–5022. <https://doi.org/10.1016/j.matpr.2021.01.450> (2021).
35. Javeed, M. A. Studies on mix design of sustainable geo-polymer concrete. *Int. J. Innov. Res. Eng. Manag.* **2**(4), 2350–0557 (2015).
36. Saini, G. & Vattipalli, U. Assessing properties of alkali activated GGBS based self-compacting geopolymer concrete using nano-silica. *Case Stud. Constr. Mater.* <https://doi.org/10.1016/j.cscm.2020.e00352> (2020).
37. Yang, T., Yao, X., Zhang, Z. & Wang, H. Mechanical property and structure of alkali-activated fly ash and slag blends. *J. Sustain. Cem. Mater.* **1**(4), 167–178. <https://doi.org/10.1080/21650373.2012.752621> (2012).
38. Khodr, M., Law, D. W., Gunasekara, C., Setunge, S. & Brkljaca, R. Compressive strength and microstructure evolution of low calcium brown coal fly ash-based geopolymer. *J. Sustain. Cem. Mater.* **9**(1), 17–34. <https://doi.org/10.1080/21650373.2019.1666061> (2020).
39. Abbass, M., Singh, G. Optimum mix design of rice husk ash-based geopolymer concrete based on workability, setting time, and compressive strength cured in ambient temperature condition, 59–74 (2022).
40. Hadi, M. N. S., Farhan, N. A. & Sheikh, M. N. Design of geopolymer concrete with GGBFS at ambient curing condition using Taguchi method. *Constr. Build. Mater.* **140**, 424–431. <https://doi.org/10.1016/j.conbuildmat.2017.02.131> (2017).
41. Hadi, M. N. S., Zhang, H. & Parkinson, S. Optimum mix design of geopolymer pastes and concretes cured in ambient condition based on compressive strength, setting time and workability. *J. Build. Eng.* **23**, 301–313. <https://doi.org/10.1016/j.jobbe.2019.02.006> (2019).

42. Modani, P. O. & Vyawahare, M. R. Utilization of bagasse ash as a partial replacement of fine aggregate in concrete. *Procedia Eng.* **51**, 25–29. <https://doi.org/10.1016/J.PROENG.2013.01.007> (2013).
43. Alrefaei, Y., Wang, Y. S. & Dai, J. G. The effectiveness of different superplasticizers in ambient cured one-part alkali activated pastes. *Cem. Concr. Compos.* **97**, 166–174. <https://doi.org/10.1016/j.cemconcomp.2018.12.027> (2019).
44. Haigh, R. et al. Microstructural attributes and physiochemical behaviours of concrete incorporating various synthetic textile and cardboard fibres: A comparative review. *J. Build. Eng.* <https://doi.org/10.1016/j.job.2024.108690> (2024).
45. Abbass, M. & Singh, G. Experimental investigation of engineered alkali-activated fibrous geopolymer concrete. *J. Build. Pathol. Rehabil.* **8**(1), 1–16. <https://doi.org/10.1007/s41024-022-00259-x> (2023).
46. Aravind, N., Nagajothi, S. & Elavenil, S. Machine learning model for predicting the crack detection and pattern recognition of geopolymer concrete beams. *Constr. Build. Mater.* <https://doi.org/10.1016/J.CONBUILDMAT.2021.123785> (2021).
47. Ponikiewski, T. & Katzer, J. Fresh mix characteristics of self-compacting concrete reinforced by fibre. *Period. Polytech. Civ. Eng.* **61**(2), 226–231. <https://doi.org/10.3311/PPci.9008> (2017).
48. Dhawan, A. & Verma, M. Durability assessment of geopolymer and OPC concretes under chloride and sulphate chemical attack. **13**(5), 2025 (2025). [Online]. Available: <https://journals.stmjournals.com/jopcl/>.
49. Upreti, K. et al. Prediction of mechanical strength by using an artificial neural network and random forest algorithm. *J. Nanomater.* <https://doi.org/10.1155/2022/7791582> (2022).
50. Han, M. Y. et al. Emergy-based hybrid evaluation for commercial construction engineering: A case study in BDA. *Ecol. Indic.* **47**, 179–188. <https://doi.org/10.1016/j.ecolind.2014.02.020> (2014).
51. Alexander, A. E. & Shashikala, A. P. Studies on the microstructure and durability characteristics of ambient cured FA-GGBS based geopolymer mortar. *Constr. Build. Mater.* <https://doi.org/10.1016/j.conbuildmat.2022.128538> (2022).
52. Abbass, M. & Singh, G. Impact strength of rice husk ash and basalt fibre based sustainable geopolymer concrete in rigid pavements. *Mater. Today Proc.* **61**, 250–257. <https://doi.org/10.1016/j.matpr.2021.09.053> (2022).
53. Abbass, M. & Singh, G. Rice husk ash and basalt fibre-based sustainable geopolymer concrete in rigid pavements. A review (2021).
54. Abbass, M. & Akhai, S. Eco-friendly geopolymer bricks synthesized from alkali-activated sugarcane bagasse ash and rice husk ash. *Ind. Crops Prod.* **233**, 121410. <https://doi.org/10.1016/j.indcrop.2025.121410> (2025).
55. Abbas, S., Kazmi, S. M. S. & Munir, M. J. Potential of rice husk ash for mitigating the alkali-silica reaction in mortar bars incorporating reactive aggregates. *Constr. Build. Mater.* **132**, 61–70. <https://doi.org/10.1016/j.conbuildmat.2016.11.126> (2017).
56. De Weerd, K., Sellevold, E., Kjellsen, K. O. & Justnes, H. Fly ash-limestone ternary cements: Effect of component fineness. *Adv. Cem. Res.* **23**(4), 203–214. <https://doi.org/10.1680/ADCR.2011.23.4.203> (2011).
57. Temuujin, J. & Darkhijav, B. Influence of basalt fibres on the properties of fly ash based, (2016). <https://doi.org/10.11629/jpaar.2016.7.1.043>.
58. Mocekis, R., Karpova, E., Kicaite, A. & Skripiunas, G. Effect of aggregates on the technological and mechanical properties of glass and basalt fibres reinforced concrete. *IOP Conf. Ser. Mater. Sci. Eng.* <https://doi.org/10.1088/1757-899X/471/3/032008> (2019).
59. Heweidak, M., Kafle, B. & Al-Ameri, R. Influence of hybrid basalt fibres' length on fresh and mechanical properties of self-compacted ambient-cured geopolymer concrete. *J. Compos. Sci.* <https://doi.org/10.3390/JCS6100292> (2022).
60. Sharma, U. et al. Behavior of fibers in geopolymer concrete: A comprehensive review. *Buildings* <https://doi.org/10.3390/BUILD1NGS14010136> (2024).
61. Barbosa, V. F. F., MacKenzie, K. J. D. & Thaumaturgo, C. Synthesis and characterisation of materials based on inorganic polymers of alumina and silica: sodium polysialate polymers. *Int. J. Inorg. Mater.* **2**(4), 309–317. [https://doi.org/10.1016/S1466-6049\(00\)00041-6](https://doi.org/10.1016/S1466-6049(00)00041-6) (2000).
62. Liu, C., Li, Z., Nie, S., Skibsted, J. & Ye, G. Structural evolution of calcium sodium aluminosilicate hydrate (C-(N)-A-S-H) gels induced by water exposure: The impact of Na leaching. *Cem. Concr. Res.* <https://doi.org/10.1016/j.cemconres.2024.107432> (2024).
63. Marsh, H. N. et al. Measurement of properties of fiber reinforced concrete. *Publ. SP Am. Concr. Inst.* **89**(Reapproved), 433–439 (1984).
64. Pham, D. Q., Nguyen, T. N., Le, S. T., Pham, T. T. & Ngo, T. D. The structural behaviours of steel reinforced geopolymer concrete beams: An experimental and numerical investigation. *Structures* **33**, 567–580. <https://doi.org/10.1016/J.ISTRUC.2021.04.077> (2021).
65. Roghanian, N. & Banthia, N. Development of a sustainable coating and repair material to prevent bio-corrosion in concrete sewer and waste-water pipes. *Cem. Concr. Compos.* **100**, 99–107. <https://doi.org/10.1016/j.cemconcomp.2019.03.026> (2019).
66. Suresh Kumar, A., Muthukannan, M., Arun Kumar, K., Chithambar Ganesh, A. & Kanniga Devi, R. Influence of incinerated biomedical waste ash and waste glass powder on the mechanical and flexural properties of reinforced geopolymer concrete. *Aust. J. Struct. Eng.* **23**(3), 254–268. <https://doi.org/10.1080/13287982.2022.2044613> (2022).
67. Lelpep, K. The effect of basalt fibre on the properties of normal-weight concrete, no. January (2016).
68. Abbass, M. & Akhai, S. Exploring the sustainability potential of geopolymer concrete with coal bottom ash and basalt fibres. *Multiscale Multidiscip. Model. Exp. Des.* **8**(3), 199. <https://doi.org/10.1007/s41939-025-00794-3> (2025).
69. Ryu, G. S., Lee, Y. B., Koh, K. T. & Chung, Y. S. The mechanical properties of fly ash-based geopolymer concrete with alkaline activators. *Constr. Build. Mater.* **47**, 409–418. <https://doi.org/10.1016/j.conbuildmat.2013.05.069> (2013).
70. Cintura, E., Nunes, L., Esteves, B. & Faria, P. Agro-industrial wastes as building insulation materials: A review and challenges for Euro-Mediterranean countries. *Ind. Crops Prod.* <https://doi.org/10.1016/J.INDCROP.2021.113833> (2021).
71. Aygörmec, Y., Canpolat, O. & Al-mashhadani, M. M. Assessment of geopolymer composites durability at one year age. *J. Build. Eng.* <https://doi.org/10.1016/j.job.2020.101453> (2020).
72. Al-Majidi, M. H., Lampropoulos, A. & Cundy, A. B. Tensile properties of a novel fibre reinforced geopolymer composite with enhanced strain hardening characteristics. *Compos. Struct.* <https://doi.org/10.1016/j.compstruct.2017.01.085> (2017).
73. Daniel, A. J., Sivakamasundari, S. & Abhilash, D. Comparative study on the behaviour of geopolymer concrete with hybrid fibers under static cyclic loading. *Procedia Eng.* **173**, 417–423. <https://doi.org/10.1016/J.PROENG.2016.12.041> (2017).
74. Hassan, A., Arif, M. & Shariq, M. Mechanical behaviour and microstructural investigation of geopolymer concrete after exposure to elevated temperatures. *Arab. J. Sci. Eng.* **45**(5), 3843–3861. <https://doi.org/10.1007/S13369-019-04269-9> (2020).
75. Abbass, M. & Singh, G. Durability of rice husk ash and basalt fibre based sustainable geopolymer concrete in rigid pavements. *Mater. Today Proc.* **61**, 558–570. <https://doi.org/10.1016/j.matpr.2022.02.196> (2022).
76. Asrani, N. P. et al. A feasibility of enhancing the impact resistance of hybrid fibrous geopolymer composites: Experiments and modelling. *Constr. Build. Mater.* **203**, 56–68. <https://doi.org/10.1016/j.conbuildmat.2019.01.072> (2019).
77. Noushini, A., Hastings, M., Castel, A. & Aslani, F. Mechanical and flexural performance of synthetic fibre reinforced geopolymer concrete. *Constr. Build. Mater.* **186**, 454–475. <https://doi.org/10.1016/j.conbuildmat.2018.07.110> (2018).
78. Guo, X. & Pan, X. Mechanical properties and mechanisms of fiber reinforced fly ash–steel slag based geopolymer mortar. *Constr. Build. Mater.* **179**, 633–641. <https://doi.org/10.1016/J.CONBUILDMAT.2018.05.198> (2018).
79. Dhanam, M. & Eswari, S. Performance evaluation of hybrid fibre reinforced concrete with polyolefin and basalt fibres. *Adv. Nat. Appl. Sci.* **11**(9), 291–296 (2017).
80. Yu, B., Gu, X., Wu, M. & Ni, F. Application of a high percentage of reclaimed asphalt pavement in an asphalt mixture: Blending process and performance investigation. *Road Mater. Pavement Des.* **18**(3), 753–765. <https://doi.org/10.1080/14680629.2016.1182941> (2017).

81. Verma, M. & Dev, N. Effect of liquid to binder ratio and curing temperature on the engineering properties of the geopolymer concrete. *Silicon* **14**(4), 1743–1757. <https://doi.org/10.1007/s12633-021-00985-w> (2022).
82. Alomayri, T., Shaikh, F. U. A. & Low, I. M. Thermal and mechanical properties of cotton fabric-reinforced geopolymer composites. *J. Mater. Sci.* **48**(19), 6746–6752. <https://doi.org/10.1007/S10853-013-7479-2> (2013).
83. Abbass, M. & Singh, G. Impact strength of rice husk ash and basalt fibre based sustainable geopolymer concrete in rigid pavements. *Mater. Today Proc.* <https://doi.org/10.1016/j.matpr.2021.09.053> (2021).
84. Sateshkumar, S. K. et al. Impact resistance of high strength chopped basalt fibre-reinforced concrete. *Rev. la Constr.* **17**(2), 240–249. <https://doi.org/10.7764/RDLC.17.2.240> (2018).
85. Deb, P. S., Sarker, P. K. & Nath, P. Sulphate resistance of slag blended fly ash based geopolymer concrete, no. October (2013).
86. Pradhan, P., Dwibedy, S., Pradhan, M., Panda, S. & Panigrahi, S. K. Durability characteristics of geopolymer concrete—Progress and perspectives. *J. Build. Eng.* **59**, 105100. <https://doi.org/10.1016/J.JOBE.2022.105100> (2022).
87. Singh, A. et al. Durability assessment of mechanochemically activated geopolymer concrete with a low molarity alkali solution. *Case Stud. Constr. Mater.* <https://doi.org/10.1016/j.cscm.2023.e02715> (2024).
88. Dhawan, A. & Verma, M. Investigation of sulphate, alkali and carbonation chemical attack in GGBS-based geopolymer concrete and OPC concrete, 2810 (2025).
89. Verma, M., Meena, R. K., Khan, M. I. & Khatib, J. M. Analysis of the effect of curing and mixing periods on mechanical properties of the geopolymer composite. *Mater. Sci.* **42**(4), 131–147. <https://doi.org/10.2478/msp-2024-0050> (2024).
90. Trindade, A. C. C., Silva, F. A., Alcamand, H. A. & Borges, P. H. R. On the durability behavior of natural fiber reinforced geopolymers. *Ceram. Eng. Sci. Proc.* **38**(3), 215–228. <https://doi.org/10.1002/9781119474746.ch20> (2018).
91. Frazão, C., Camões, A., Barros, J. & Gonçalves, D. Durability of steel fiber reinforced self-compacting concrete. *Constr. Build. Mater.* **80**, 155–166. <https://doi.org/10.1016/j.conbuildmat.2015.01.061> (2015).
92. Zhang, S. P. & Zong, L. Evaluation of relationship between water absorption and durability of concrete materials. *Adv. Mater. Sci. Eng.* <https://doi.org/10.1155/2014/650373> (2014).
93. Granju, J. L. & Balouch, S. U. Corrosion of steel fibre reinforced concrete from the cracks. *Cem. Concr. Res.* **35**(3), 572–577. <https://doi.org/10.1016/j.cemconres.2004.06.032> (2005).
94. Wong, L. S. Durability performance of geopolymer concrete: A review. *Polymers (Basel)* <https://doi.org/10.3390/POLYM14050868> (2022).
95. Amin, M., Zeyad, A. M., Tayeh, B. A. & Saad Agwa, I. Engineering properties of self-cured normal and high strength concrete produced using polyethylene glycol and porous ceramic waste as coarse aggregate. *Constr. Build. Mater.* <https://doi.org/10.1016/j.conbuildmat.2021.124243> (2021).
96. Rukzon, S. & Chindaprasit, P. Utilization of bagasse ash in high-strength concrete. *Mater. Des.* **34**, 45–50. <https://doi.org/10.1016/j.matdes.2011.07.045> (2012).
97. Joshaghani, A. & Moeini, M. A. Evaluating the effects of sugarcane-bagasse ash and rice-husk ash on the mechanical and durability properties of mortar. *J. Mater. Civ. Eng.* [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002317](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002317) (2018).
98. Wang, B., Yan, L., Fu, Q. & Kasal, B. A comprehensive review on recycled aggregate and recycled aggregate concrete. *Resour. Conserv. Recycl.* <https://doi.org/10.1016/j.resconrec.2021.105565> (2021).
99. Alsaif, A. et al. Fatigue performance of flexible steel fibre reinforced rubberised concrete pavements. *Eng. Struct.* **193**, 170–183. <https://doi.org/10.1016/j.engstruct.2019.05.040> (2019).
100. Nikmehr, B., Kafle, B., Al Zand, A. W. & Al-Ameri, R. The effect of hybrid basalt fibres on the mechanical and structural characteristics of geopolymer concrete containing geopolymer-coated recycled concrete aggregates. *Constr. Build. Mater.* **450**, 138649. <https://doi.org/10.1016/J.CONBUILDMAT.2024.138649> (2024).
101. Aliabdo, A. A. E., Abd-Elmoaty, A. E. M. & Hamdy, M. Effect of internal short fibers, steel reinforcement, and surface layer on impact and penetration resistance of concrete. *Alex. Eng. J.* **52**(3), 407–417. <https://doi.org/10.1016/j.aej.2013.06.002> (2013).
102. Maruthupandian, S. Durability studies on basalt fibre reinforced concrete, no. June (2018).
103. Wang, B., Yan, L. & Kasal, B. A review of coir fibre and coir fibre reinforced cement-based composite materials (2000–2021). *J. Clean. Prod.* <https://doi.org/10.1016/j.jclepro.2022.130676> (2022).
104. Kirthika, S. K. & Singh, S. K. Experimental investigations on basalt fibre-reinforced concrete. *J. Inst. Eng. Ser. A* **99**(4), 661–670. <https://doi.org/10.1007/s40030-018-0325-4> (2018).

Author contributions

Govind Ravish: Writing, experimentation, literature review. Dr Mahapara Abbass: Guide, validation. I transfer the non-exclusive publication rights, Dr Mahapara Abbass, to the Scientific Reports. I also guarantee that my contribution is unique and that I have the legal authority to make this contribution. On behalf of all co-authors, I assume liability for publishing this work. The non-exclusive right to reproduce and distribute the article under these publication rights includes reprints, photographic reproductions, translations, microform, electronic form (offline, online), and any other reproductions of the same type.

Declarations

Ethical approval

The manuscript entitled “Engineering Properties of Fibrous Agro-Waste-Based Geopolymer Concrete for Sustainable Future Construction”. It has not been simultaneously submitted for publication anywhere else, and it has not been published elsewhere. Moreover, “I have not submitted my manuscript to a preprint server before submitting it to the Scientific Reports”.

Competing interests

The authors declare no competing interests.

Additional information

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