
Evaluation of Mechanical and Durability Properties of Polypropylene-Basalt Hybrid Fibre-Reinforced Concrete

Ram Bhupal Reddy Anna Reddy^{1, 2, *}, Jayarami Reddy Bommi Reddy²

¹Department of Civil Engineering, Rajiv Gandhi University of Knowledge Technologies, Rajiv Knowledge Valley, India

²Department of Civil Engineering, YSR Engineering College of Yogi Vemana University, Proddatur, India

Email address:

bhupal@rguktrkv.ac.in. (Ram Bhupal Reddy Anna Reddy), bjiyreddyyvuce@gmail.com (Jayarami Reddy Bommi Reddy)

To cite this article:

Ram Bhupal Reddy Anna Reddy, Jayarami Reddy Bommi Reddy. (2026). Evaluation of Mechanical and Durability Properties of Polypropylene-Basalt Hybrid Fibre-Reinforced Concrete. *American Journal of Civil Engineering*, 14(5), 370-381.

<https://doi.org/10.11648/j.ajam.20261405.17>

Received: 3 September 2026; **Accepted:** 3 September 2026 **Published:** 12 October 2026

Abstract: Hybrid fibre-reinforced concrete is an effective approach for improving the mechanical performance, deformation capacity, and durability of concrete by combining fibres with complementary mechanical characteristics. Basalt fibres provide high stiffness and tensile strength, whereas polypropylene fibres contribute to crack control and post-cracking deformation. However, the combined influence of total hybrid fibre volume and fibre proportion on the mechanical and durability performance of polypropylene-basalt hybrid fibre-reinforced concrete requires further investigation. Therefore, this study experimentally evaluates the mechanical and durability properties of M40-grade polypropylene-basalt hybrid fibre-reinforced concrete with different total fibre volume fractions and fibre proportions. Twelve hybrid mixtures were prepared by varying the total fibre volume from 0.25% to 1.0% and the polypropylene-to-basalt fibre ratio as 25:75, 50:50, and 75:25, along with a plain concrete control mix. Compressive and flexural strengths were evaluated at 3, 7, 28, and 90 days, while splitting tensile strength and water absorption were assessed at 28 days. Compressive stress-strain behaviour and deformation characteristics were also examined. The results showed that compressive strength was most effective at low to moderate fibre contents of 0.25-0.50%, particularly in basalt-rich mixtures, whereas higher fibre contents reduced compressive strength because of fibre interaction, reduced workability, and dispersion limitations. Flexural strength and deformation capacity improved substantially with hybrid fibre incorporation, with basalt-rich mixtures providing higher peak strength and polypropylene fibres contributing to post-cracking deformation. The 28-day splitting tensile strength increased by nearly 30% at 0.75% total fibre volume in the basalt-rich mixture. Water absorption progressively decreased with increasing fibre content, reaching a minimum of 1.07% at 1.0% total fibre volume in the basalt-rich mixture. Overall, polypropylene-basalt hybridisation effectively balances strength, ductility, tensile resistance, and durability, with the optimum fibre content depending on the targeted performance requirements.

Keywords: Hybrid Fibre-reinforced Concrete, Polypropylene Fibre, Basalt Fibre, Mechanical Properties, Flexural Behaviour, Splitting Tensile Strength, Water Absorption

1. Introduction

The incorporation of short, discrete fibres into concrete has been widely adopted as an effective strategy to mitigate brittleness and improve resistance to crack initiation and propagation. While fibre addition rarely leads to substantial increases in peak compressive strength, it significantly alters post-cracking behaviour, deformation capacity, and energy dissipation, which are critical for structural performance

and durability. Among the available synthetic and mineral fibres, basalt and polypropylene fibres have attracted increasing attention because of their availability, durability, and contrasting mechanical characteristics. Basalt fibres exhibit high elastic modulus and tensile strength, whereas polypropylene fibres possess low stiffness but high elongation capacity, making their combined use particularly attractive for hybrid fibre-reinforced concrete systems.

Previous studies consistently report that compressive

strength is less sensitive to fibre inclusion than tensile-dominated properties, regardless of fibre type. In basalt fibre-reinforced concrete, compressive strength typically increases only up to a moderate fibre dosage and may decline at higher contents due to fibre agglomeration and increased porosity, despite improved crack restraint at early loading stages [11, 17]. Polypropylene fibres exhibit an even more limited influence on peak compressive strength, instead modifying compressive damage evolution by delaying crack coalescence and increasing ultimate strain and toughness [19]. In hybrid polypropylene-basalt systems, compressive performance improves only within a narrow fibre volume range, where basalt fibres enhance elastic-stage stiffness and polypropylene fibres contribute to damage tolerance; excessive hybrid fibre contents introduce internal defects that offset these benefits [6].

Flexural performance shows a markedly stronger response to fibre reinforcement than compressive strength. Basalt fibres significantly enhance flexural strength and fracture resistance through effective crack-bridging and stress redistribution, with improvements peaking at an optimum fibre dosage beyond which dispersion issues reduce efficiency [16, 23]. Polypropylene fibres primarily influence flexural behaviour by improving post-cracking response, residual load-carrying capacity, and toughness through fibre pull-out mechanisms rather than by increasing peak strength [14]. Hybrid polypropylene-basalt systems demonstrate a clear synergistic effect under flexural loading, as high-modulus basalt fibres restrain micro-crack initiation while polypropylene fibres sustain load transfer at larger crack openings, resulting in enhanced flexural strength and fracture energy at moderate hybrid fibre volumes [7, 13].

Splitting tensile strength is consistently reported as one of the most fibre-sensitive properties of concrete. Basalt fibres substantially improve tensile resistance by bridging micro-cracks and redistributing tensile stresses, with strength gains increasing up to an optimum fibre content and diminishing thereafter due to clustering and increased void content [2]. Polypropylene fibres also enhance tensile behaviour, although their contribution is primarily associated with crack control and post-peak deformation rather than peak tensile strength. In hybrid systems, tensile performance benefits from the complementary action of both fibres, where basalt fibres improve crack initiation resistance and polypropylene fibres govern crack propagation and energy absorption, leading to superior tensile response compared with mono-fibre concretes [20].

Durability-related performance exhibits a non-linear relationship with fibre content. Moderate basalt fibre dosages have been shown to improve resistance to aggressive environments, including freeze-thaw cycles, high temperatures, and chloride exposure, by refining pore structure and limiting crack connectivity, although water absorption may increase slightly because of fibre-matrix interfacial voids [1, 15]. Polypropylene fibres display a dual influence on durability: while they may increase permeability in uncracked concrete due to increased pore connectivity, they significantly

reduce permeability under cracked or cyclic loading conditions by restricting crack width and enhancing crack tortuosity [12, 22]. Hybrid polypropylene-basalt systems exhibit improved durability only within an optimum fibre volume range, where crack control benefits outweigh fibre-induced porosity, whereas excessive hybridisation adversely affects water absorption and permeability [24].

Although extensive research exists on basalt fibres, polypropylene fibres, and their hybridisation, most studies focus on a single fibre dosage or a fixed fibre proportion, often evaluating isolated performance indicators. Integrated investigations that simultaneously assess compressive stress-strain behaviour, flexural response, splitting tensile strength and water absorption within a consistent experimental framework remain limited. Consequently, the combined influence of total hybrid fibre volume and fibre proportion on mechanical performance and durability has not been systematically established.

To address these limitations, the present study investigates polypropylene-basalt hybrid fibre-reinforced concrete using total hybrid fibre volume fractions of 0.25 %, 0.50%, 0.75%, and 1.0%, with polypropylene-to-basalt fibre proportions of 25:75, 50:50, and 75:25, alongside a plain control mix. The study evaluates compressive and flexural stress-strain behaviour, splitting tensile strength, and water absorption with the objective of identifying the optimum hybrid fibre volume and fibre proportion that govern the mechanical performance and durability of the concrete.

2. Materials and Methodology

2.1. Constituent Materials

Ordinary Portland Cement conforming to IS 8112:2013 (43-grade) was used as the primary binder. The cement exhibited a specific gravity of 3.15 and a standard consistency of approximately 30%. Natural river sand complying with Zone II grading requirements of IS 383:2016 served as the fine aggregate, while crushed granite with a nominal maximum size of 20 mm was used as the coarse aggregate. The specific gravities of fine and coarse aggregates were 2.64 and 2.75, respectively, with water absorption values below 1%. Potable water was used for both mixing and curing processes.

A polycarboxylate-based superplasticizer was incorporated at a dosage of 0.8% by weight of cement to achieve the required workability at a constant water-binder ratio. Basalt fibres used in this study were 24 mm chopped monofilament fibres derived from molten basalt rock, with a nominal diameter of 13-20 μm , tensile strength of 2.8-4.1 GPa (GPa), and elastic modulus of 85-95 GPa. Their high stiffness, chemical stability, and thermal resistance make them suitable for structural concrete applications. When uniformly dispersed, they enhance crack-bridging capacity and improve post-peak energy absorption and toughness. The polypropylene fibres are macro-synthetic Fibre-Tuff strands, with length of 54 mm and an equivalent diameter of 0.8-

0.9 mm. They carried tensile strengths of around 550-650 Megapascal (MPa) and a modulus between 5 and 9 GPa. These fibres had embossed surfaces that improved anchorage. Their light weight, flexibility and ability to disperse in multiple directions helped control micro-cracking and improve the post-peak response of the concrete.

The use of basalt and polypropylene fibres in combination enabled the investigation of hybrid fibre action involving a stiff, high-strength fibre and a ductile, low-stiffness fibre within the same cementitious matrix. All fibres were incorporated on a volumetric basis and were dry-mixed with aggregates prior to the addition of water to promote uniform dispersion and minimise fibre agglomeration.

2.2. Mix Proportions and Experimental Variables

All concrete mixes were proportioned to achieve M40 grade strength, corresponding to a target mean compressive strength

of 48.25 MPa. A constant water-binder ratio of 0.41 was maintained for all mixtures to isolate the influence of fibre addition. The experimental variables consisted of the total fibre volume fraction and the proportion of polypropylene fibre to basalt fibre within the hybrid system.

Total fibre volume fractions of 0.25%, 0.50%, 0.75%, and 1.00% were investigated. For each fibre volume level, polypropylene-to-basalt fibre ratios of 25:75, 50:50, and 75:25 were adopted, resulting in twelve hybrid fibre-reinforced concrete mixes. In addition, a control mix without fibres was prepared for reference. The absolute quantities of cement, aggregates, water, and superplasticizer were kept constant across all mixes, corresponding to the control M40 mix design, and were not repeated to avoid redundancy. The mix identification and fibre combinations are summarised in Table 1.

Table 1. Mix proportions and hybrid fibre combinations used in the study.

Mix ID	Total fibre volume (%)	PP fibre volume (%)	Basalt fibre volume (%)	Hybrid type
Control	0.00	0.00	0.00	Plain concrete
M1	0.25	0.07	0.18	Basalt-rich (low fibre)
M2	0.25	0.125	0.125	Balanced (low fibre)
M3	0.25	0.18	0.07	PP-rich (low fibre)
M4	0.50	0.125	0.375	Basalt-rich (medium fibre)
M5	0.50	0.250	0.250	Balanced (medium fibre)
M6	0.50	0.375	0.125	PP-rich (medium fibre)
M7	0.75	0.19	0.56	Basalt-rich (high fibre)
M8	0.75	0.375	0.375	Balanced (high fibre)
M9	0.75	0.56	0.19	PP-rich (high fibre)
M10	1.00	0.25	0.75	Basalt-rich (very high fibre)
M11	1.00	0.50	0.50	Balanced (very high fibre)
M12	1.00	0.75	0.25	PP-rich (very high fibre)

2.3. Specimen Preparation and Curing

Concrete mixing was carried out using a laboratory pan mixer. Initially, cement and aggregates were dry-mixed for approximately one minute to ensure uniform distribution. Fibres were then introduced gradually in small increments, particularly for higher fibre volume fractions, to minimise balling and ensure homogeneous dispersion. Subsequently, water mixed with the required dosage of superplasticizer was added, and mixing was continued until a uniform consistency was achieved.

Workability of the fresh concrete was assessed using the slump test in accordance with IS 1199:1959. Specimens were cast in steel moulds, compacted using mechanical vibration, and covered with moist burlap for the first 24 hours. After demoulding, all specimens were cured in water at ambient laboratory temperature until the designated testing ages.

2.4. Testing Programme

2.4.1. Mechanical Properties

Compressive strength tests were conducted on 150 mm cube specimens in accordance with IS 516 (Part 1):2021. Flexural strength was evaluated using $150 \times 150 \times 700$ mm prism specimens subjected to two-point loading, following IS 516 (Part 2):2021. Splitting tensile strength was determined on cylindrical specimens measuring 150 mm in diameter and 300 mm in height, as per IS 5816:1999.

Compressive and flexural strength tests were performed at curing ages of 3, 7, 28, and 90 days, while splitting tensile strength was evaluated at 28 days. For each test and age, three replicate specimens were tested, and the reported values represent the average of these measurements.

2.4.2. Durability Assessment

Durability performance was assessed through water absorption measurements in accordance with IS 3085:2020. Cube specimens were oven-dried to a constant mass and

subsequently immersed in water for 48 hours. Water absorption was calculated as the percentage increase in mass relative to the dry weight. This parameter was selected as it provides a direct indication of pore structure connectivity and matrix densification resulting from fibre incorporation.

2.5. Data Reliability and Quality Control

To ensure data reliability, all mechanical test results were evaluated in terms of statistical variation. The coefficient of variation for the majority of test results remained within 5%, indicating good repeatability. In isolated cases where the variation marginally exceeded this limit, additional specimens were tested to confirm the consistency of the reported mean values. Accordingly, all results presented in subsequent sections represent statistically reliable averages.

3. Results And Discussion

3.1. Compressive Strength

The compressive strength of polypropylene-basalt (PP-BF) hybrid fibre-reinforced concrete was evaluated at curing ages of 3, 7, 28, and 90 days for different total fibre volumes and PP:BF proportions. The results presented in Table 2 indicate that compressive strength response is strongly dosage-dependent, with no continuous strength enhancement achieved through increasing fibre content. The variation of compressive strength for different mixes and curing ages is illustrated in Figure 1. Similar non-monotonic behaviour has been reported for hybrid PP-BF systems, where fibre synergy is effective only within a limited dosage range [6].

Table 2. Compressive Strength and Deformation Values of Basalt–Polypropylene Hybrid Fibre-Reinforced Concrete at Different Curing Ages.

Mix	Total fibre vol. (%)	PP fibre vol. (%)	Basalt fibre vol. (%)	Comp. strength 3 days (MPa)	Comp. strength 7 days (MPa)	Comp. strength 28 days (MPa)	Comp. strength 90 days (MPa)	Strain at peak stress 28 days	Strain at failure 28 days
Control	0.00	0.00	0.00	24.10	34.64	50.20	56.22	0.0021	0.0033
M1	0.25	0.07	0.18	25.31	36.96	51.71	60.52	0.0025	0.0042
M2	0.25	0.125	0.125	24.83	35.97	51.20	58.90	0.0024	0.0047
M3	0.25	0.18	0.07	24.58	35.65	50.70	57.87	0.0023	0.0049
M4	0.50	0.125	0.375	24.34	35.54	50.20	57.57	0.0028	0.0048
M5	0.50	0.250	0.250	23.85	34.79	49.20	55.87	0.0026	0.0053
M6	0.50	0.375	0.125	23.37	33.75	48.19	54.68	0.0025	0.0060
M7	0.75	0.19	0.56	23.37	34.08	48.19	55.27	0.0029	0.0052
M8	0.75	0.375	0.375	22.64	32.79	46.69	53.02	0.0028	0.0062
M9	0.75	0.56	0.19	22.15	31.99	45.68	51.78	0.0026	0.0074
M10	1.00	0.25	0.75	22.64	32.76	46.69	53.54	0.0031	0.0059
M11	1.00	0.50	0.50	21.91	31.61	45.18	51.46	0.0030	0.0070
M12	1.00	0.75	0.25	21.18	30.47	43.67	49.45	0.0027	0.0081

At early ages (3 and 7 days), fibre-reinforced mixes exhibited compressive strengths comparable to the control concrete, irrespective of fibre volume or proportion. This indicates that early-age compressive strength is governed primarily by cement hydration and matrix development, while fibres contribute minimally before effective fibre-matrix bonding is established. The limited influence of fibres at early ages is consistent with observations reported for hybrid fibre-reinforced concretes incorporating polymeric fibres [8].

At 28 days, a clear dosage-dependent trend was observed. Hybrid concretes with total fibre volumes of 0.25-0.50% achieved compressive strengths comparable to or marginally higher than the control mix. Within this range, basalt-rich combinations consistently outperformed balanced and polypropylene-rich mixes. This behaviour is attributed to the high elastic modulus and tensile strength of basalt

fibres, which enhance internal restraint and delay microcrack coalescence under compressive loading. Similar stabilisation of compressive strength at moderate basalt fibre contents has been reported in basalt fibre-reinforced concretes [20].

When the total fibre volume exceeded 0.50%, compressive strength decreased progressively, regardless of fibre proportion. At higher dosages greater or equal to 0.75%, fibre agglomeration, reduced workability, and increased entrapped air adversely affected matrix compactness, leading to inefficient stress transfer. These effects were more pronounced in polypropylene-rich mixes due to the lower stiffness of polypropylene fibres contribute limited direct resistance to compressive load. Comparable reductions in compressive strength at high fibre volumes have been reported in hybrid systems containing flexible fibres [8].

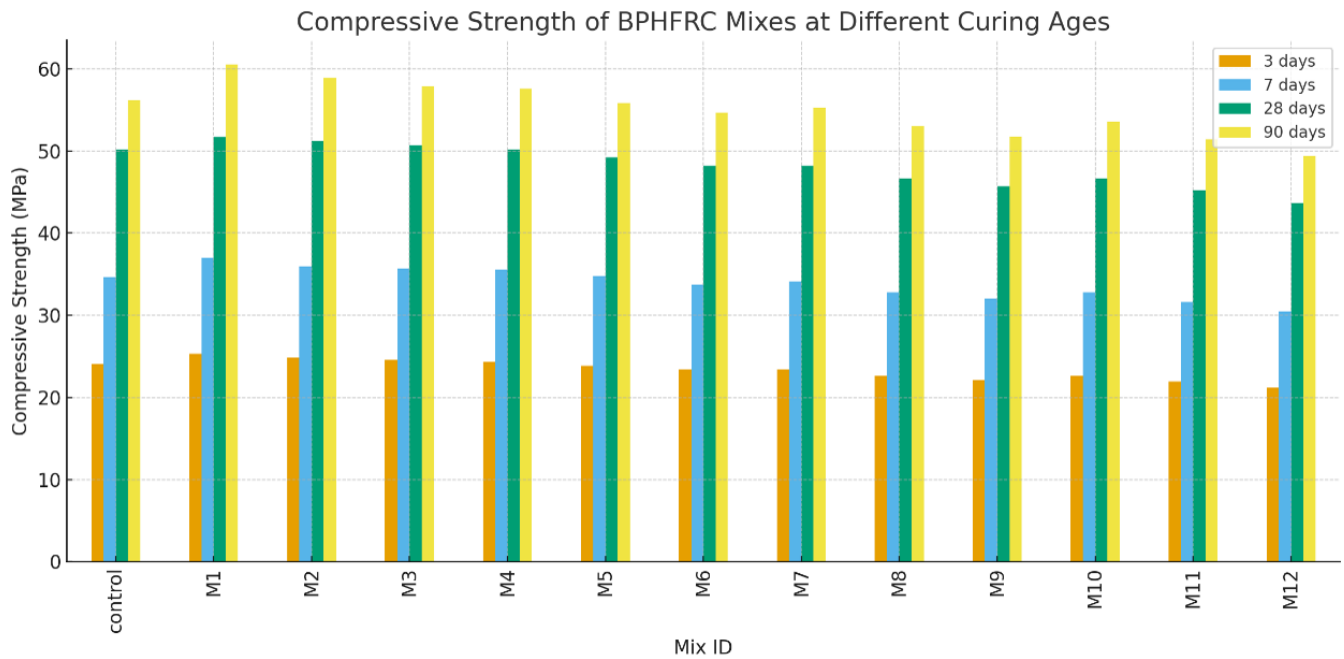


Figure 1. Bar Chart Showing Compressive Strength of Control and Basalt–Polypropylene Hybrid Fibre-Reinforced Concrete Mixes at Different Curing Ages.

At 90 days, all mixes continued to gain strength, confirming that fibre addition did not inhibit long-term hydration. However, the relative ranking remained unchanged, with low-dosage, basalt-dominant hybrids exhibiting the highest strengths. These results indicate that optimal compressive performance is achieved at total fibre volumes of 0.25–0.50%, beyond which matrix disruption outweighs fibre-related benefits [6].

Stress-strain response and deformation characteristics: Hybrid fibre incorporation significantly modified the stress-strain response of concrete under uniaxial compression, particularly in the post-peak regime. The control concrete exhibited a brittle response characterised by abrupt stress reduction after peak load, whereas all fibre-reinforced concretes showed enhanced deformation capacity and more gradual post-peak softening.

The strain at peak stress increased moderately with fibre addition, indicating delayed crack localisation and improved internal restraint. Basalt-rich hybrids exhibited higher peak strains than the control, reflecting the contribution of high-stiffness fibres in enhancing pre-peak confinement. In contrast, polypropylene-rich hybrids displayed substantially higher strains at failure, highlighting their effectiveness in bridging wider cracks and sustaining post-peak deformation.

Although peak compressive stress decreased at higher fibre volumes, deformation capacity increased markedly. Polypropylene-dominant mixes exhibited failure strains more than twice that of the control concrete, confirming a transition from brittle splitting to progressive crushing. Similar enhancements in post-peak deformation and energy dissipation have been reported for hybrid fibre concretes combining stiff and flexible fibres [8].

The observed stress-strain behaviour can be explained

by staged fibre activation. Basalt fibres are mobilised at lower strain levels due to their high stiffness, contributing to crack delay and stiffness retention. As cracking progresses, polypropylene fibres become increasingly effective in controlling crack opening and redistributing stresses, thereby governing post-peak response. This complementary interaction provides a mechanistic basis for the improved ductility of hybrid systems.

Implications for hybrid fibre optimization: The combined evaluation of compressive strength and deformation behaviour demonstrates that PP-BF hybrid concrete should be proportioned based on performance objectives rather than maximising fibre content. For applications prioritising compressive strength retention, total fibre volumes of 0.25–0.50% with basalt-rich proportions are optimal. Conversely, where enhanced deformation capacity and damage tolerance are required, higher fibre volumes with increased polypropylene content may be justified despite moderate strength reductions. By systematically varying fibre dosage and proportion, this study provides a rational basis for optimising hybrid fibre systems to achieve balanced strength and ductility in structural concrete applications.

3.2. Flexural Behavior

Age-wise flexural strength development: The flexural strength results are presented in Table 3. Flexural behaviour of polypropylene-basalt hybrid fibre-reinforced concrete (PP-BF HFRC) demonstrated consistent improvement over the control concrete at all curing ages, confirming the effectiveness of hybrid fibre action under bending. The extent of enhancement was influenced by curing age, total fibre volume fraction, and the relative proportion of polypropylene and basalt fibres.

Table 3. Flexural Strength and Deflection Characteristics of PP-BF Hybrid Fibre-Reinforced Concrete at Different Curing Ages.

Mix	Total Fibre Vol. (%)	PP Fibre Vol. (%)	Basalt Fibre Vol. (%)	Flexural Strength 3 Days (MPa)	Flexural Strength 7 Days (MPa)	Flexural Strength 28 Days (MPa)	Flexural Strength 90 Days (MPa)	Deflection at Peak Load (mm)	Maximum Deflection at Failure (mm)
Control	0.00	0.00	0.00	2.04	3.16	4.86	5.35	1.68	1.75
M1	0.25	0.07	0.18	2.37	3.63	5.80	6.24	1.94	2.07
M2	0.25	0.125	0.125	2.24	3.43	5.40	5.88	1.87	2.07
M3	0.25	0.18	0.07	2.13	3.27	5.08	5.55	1.75	2.06
M4	0.50	0.125	0.375	2.55	3.87	6.33	6.74	2.21	2.53
M5	0.50	0.250	0.250	2.48	3.77	6.08	6.51	2.04	2.58
M6	0.50	0.375	0.125	2.31	3.53	5.62	6.08	1.88	2.55
M7	0.75	0.19	0.56	2.88	4.36	7.10	7.44	2.55	3.05
M8	0.75	0.375	0.375	2.63	4.01	6.48	7.00	2.29	3.15
M9	0.75	0.56	0.19	2.46	3.74	5.97	6.49	1.99	3.10
M10	1.00	0.25	0.75	2.92	4.44	7.17	7.59	2.67	3.41
M11	1.00	0.50	0.50	2.72	4.10	6.82	7.12	2.37	3.52
M12	1.00	0.75	0.25	2.54	3.86	6.17	6.72	2.06	3.47

At 3 days, the control mix exhibited a flexural strength of 2.04 MPa, while hybrid mixes ranged from 2.13 to 2.92 MPa, corresponding to improvements of approximately 4-43%. At this early stage, matrix hydration is incomplete; thus, the enhancement primarily results from fibre-induced crack arrest and stress redistribution rather than matrix densification. Basalt-dominant mixes consistently produced higher strength than polypropylene-rich combinations at identical fibre volumes, reflecting the higher elastic modulus of basalt fibres and their greater efficiency in resisting crack initiation. A similar enhancement of pre-cracking flexural response due to basalt fibre incorporation has been reported by [5].

At 7 days, the control strength increased to 3.16 MPa, while hybrid mixes achieved values between 3.27 and 4.44 MPa. The relative ranking remained consistent, confirming that basalt fibres effectively contribute to stiffness and delay crack propagation under bending.

A pronounced improvement was observed at 28 days. The control mix reached 4.86 MPa, whereas hybrid mixes attained 5.08-7.17 MPa, with the maximum increase approaching 48%. The highest strengths were obtained for basalt-dominant systems at 0.75-1.0% fibre volume, indicating that basalt fibres primarily govern peak load capacity. Balanced combinations provided slightly lower but comparable values, demonstrating effective hybrid interaction. The nonlinear increase beyond 0.75% fibre volume suggests the onset of fibre interaction and dispersion limitations, which reduce incremental stress-transfer efficiency. Similar saturation behaviour in hybrid

systems has been discussed by [3].

At 90 days, continued hydration further increased flexural strength, with hybrid mixes reaching up to 7.59 MPa compared to 5.35 MPa for the control. Importantly, the ranking of fibre combinations remained largely unchanged from 28 days, indicating that long-term matrix development enhances absolute strength without altering the dominant role of fibre type in governing flexural performance.

Deflection Behaviour and Flexural Toughness: The incorporation of PP-BF hybrid fibres markedly improved deformation capacity compared with the brittle control mix. The plain specimen showed limited peak (1.68 mm) and failure deflection (1.75 mm), whereas all hybrid mixes exhibited substantially higher values.

Peak deflection increased consistently with total fibre volume, reaching 2.55 mm at 0.75% and 2.67 mm at 1.0%. At a given dosage, basalt-dominant mixes generally showed higher peak deflection than polypropylene-rich combinations, indicating improved cracking resistance and delayed stiffness degradation. Similar enhancement in pre-peak flexural response of hybrid systems has been reported [5].

Failure deflection exhibited a stronger dependence on total fibre content than on fibre proportion. At 1.0% fibre volume, failure deflection reached 3.41-3.52 mm, nearly double that of the control. Notably, balanced mixes consistently produced the highest or near-highest ultimate deflection. This trend is evident in Figure 2, which correlates 28-day flexural strength with failure deflection.

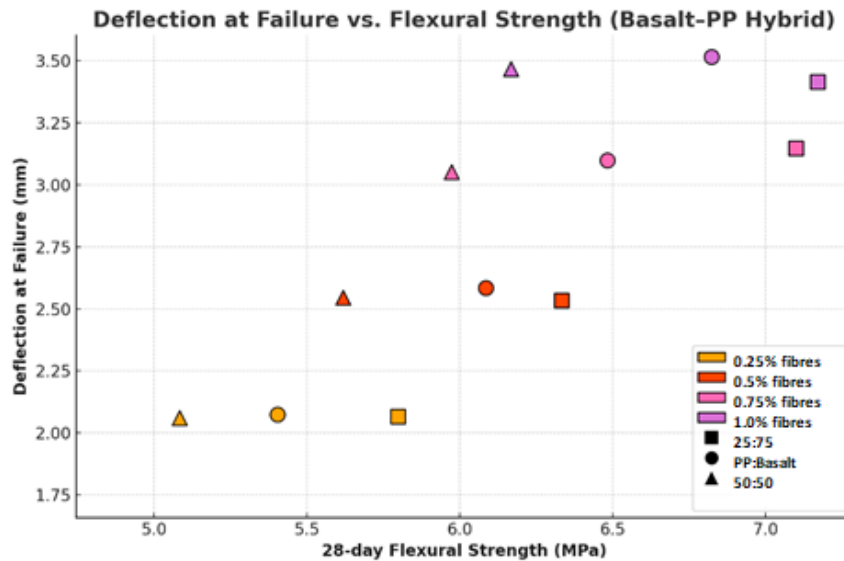


Figure 2. Correlation between 28-day flexural strength and deflection at failure for PP-BF hybrid fibre-reinforced concrete.

The observed behaviour reflects sequential fibre engagement under flexural loading. Basalt fibres, owing to their higher stiffness, increase the cracking load and thereby raise the deflection attained at peak load. After peak load is reached, polypropylene fibres become progressively mobilised, bridging wider cracks and sustaining additional post-peak deformation through pull-out mechanisms. In balanced hybrid systems, the elevated peak-deflection level provided by basalt fibres is combined with the extended post-peak deformation contributed by polypropylene fibres. As a result, the total failure deflection becomes maximum in balanced mixes. The significant contribution of polypropylene fibres to post-cracking toughness is consistent with reported findings [4].

An increase in total fibre volume from 0.75% to 1.0% resulted in only marginal improvement in flexural strength, indicating a tendency toward strength stabilisation at higher dosages. However, peak and failure deflection continued to increase at 1.0%, suggesting that additional fibre content

contributed more significantly to deformation capacity than to further strength enhancement. This divergence between strength and deformation response highlights the existence of an optimal hybrid range rather than a proportional dose-response relationship. Similar observations regarding nonlinear performance improvement in hybrid systems have been reported [3].

Implications for Hybrid Fibre Optimisation: The combined interpretation of strength (Figure 3) and strength-deflection correlation (Figure 2) indicates that flexural performance is governed by the balance between stiffness enhancement and ductility development.

Figure 3 shows that flexural strength increases significantly from 0.25% to 0.75%, with only marginal gains at 1.0%. Basalt-dominant mixes achieved the highest modulus of rupture due to superior stiffness and stress-transfer capacity. However, Figure 2 demonstrates that maximum failure deflection occurs in balanced configurations, not in the most polypropylene-rich mixes.

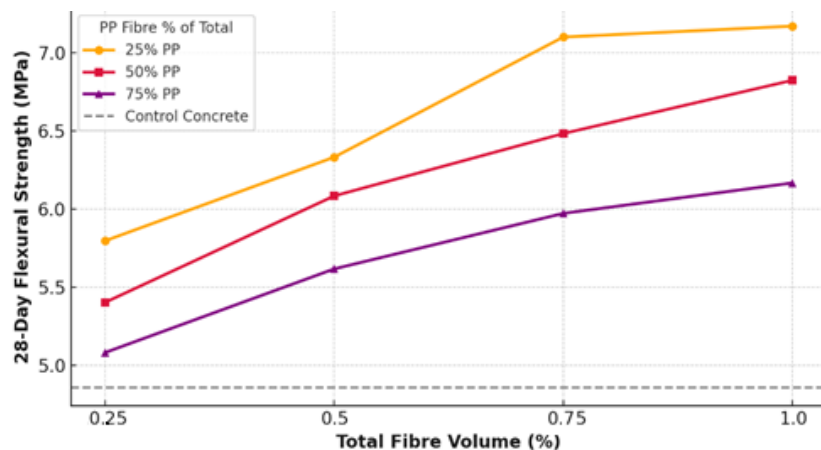


Figure 3. Variation of 28-day flexural strength with total fibre volume at different PP:BF ratios.

These findings confirm that basalt fibres primarily enhance peak load capacity, whereas polypropylene fibres govern post-cracking deformation. Balanced PP-BF combinations provide the most favourable strength-ductility compromise.

A total fibre volume of 0.75-1.0% delivers the most effective overall performance, combining significant strength enhancement with controlled ductile behaviour suitable for structural applications.

3.3. Splitting Tensile Strength

The 28-day splitting tensile strength of polypropylene-basalt (PP-BF) hybrid fibre-reinforced concrete was evaluated to quantify the enhancement in indirect tensile resistance. The results are presented in Table 4, and the variation with total fibre volume and proportion is illustrated in Figure 4.

Table 4. Splitting-Tensile Strength of PP-BF Hybrid Fibre-Reinforced Concrete (28 Days).

Mix ID	Polypropylene Fibre (%)	Basalt Fibre (%)	Total Fibre (%)	Splitting Tensile Strength (MPa)
Control	0.00	0.00	0.00	3.57
M1	0.07	0.18	0.25	4.26
M2	0.125	0.125	0.25	4.14
M3	0.18	0.07	0.25	4.03
M4	0.125	0.375	0.50	4.52
M5	0.250	0.250	0.50	4.39
M6	0.375	0.125	0.50	4.32
M7	0.19	0.56	0.75	4.63
M8	0.375	0.375	0.75	4.49
M9	0.56	0.19	0.75	4.18
M10	0.25	0.75	1.00	4.33
M11	0.50	0.50	1.00	4.19
M12	0.75	0.25	1.00	3.98

Influence of total fibre volume fraction: As shown in Table 4, the control concrete exhibited a splitting tensile strength of 3.57 MPa. The incorporation of hybrid fibres resulted in a consistent enhancement across all fibre dosages. At 0.25% total fibre volume, the tensile strength increased to 4.26 MPa (M1), corresponding to an improvement of approximately 19.3% over the control mix. The balanced (M2: 4.14 MPa) and polypropylene-dominant (M3: 4.03 MPa) mixes also demonstrated improvements of 16.0% and 12.9%, respectively, confirming that even low fibre volumes significantly enhance resistance to diametral cracking.

Further increasing the total fibre volume to 0.5% resulted in tensile strengths ranging from 4.32 to 4.52 MPa, representing enhancements of 21-27% relative to the control. The tensile resistance continued to improve at 0.75% fibre content, where mix M7 achieved the maximum value of 4.63 MPa, corresponding to an enhancement of nearly 30%.

However, at 1.0% total fibre volume, a marginal reduction

was observed, with strengths decreasing to the range of 3.98-4.33 MPa. Although still higher than the control mix, the reduction relative to the 0.75% mixes indicates reduced reinforcement efficiency at excessive fibre dosages. This confirms the existence of an optimum fibre volume of 0.75% for maximising splitting tensile strength.

The reduction at higher fibre volumes can be attributed to diminished workability and increased fibre interaction, which may impair uniform dispersion and reduce effective stress transfer across the diametral crack plane. Similar dosage-sensitive behaviour has been reported in hybrid PP-BF concretes, where intermediate fibre contents maximised crack-bridging efficiency while excessive fibre addition reduced tensile effectiveness due to dispersion limitations [9]. Comparable observations have also been documented for basalt fibre-reinforced systems, where mechanical enhancement was governed by fibre distribution and matrix continuity [18].

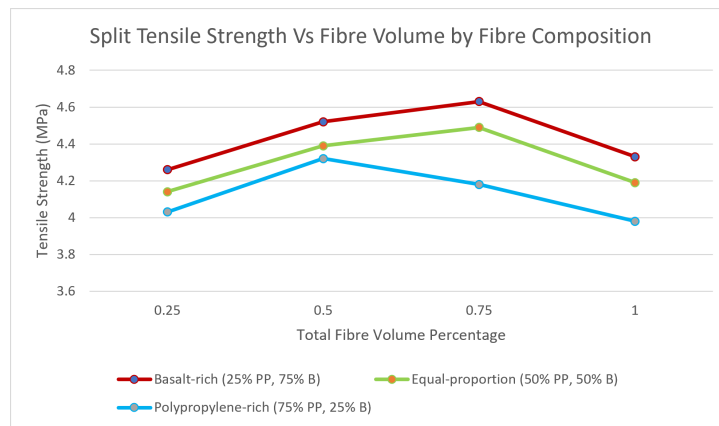


Figure 4. Variation of splitting tensile strength with total fibre content for basalt and polypropylene hybrid fibre-reinforced concrete mixes.

Effect of Fibre Proportion in Hybrid Mixes : For a constant total fibre volume, fibre proportion significantly influenced splitting tensile performance. At 0.25% total fibre content, the basalt-rich mix (M1: 4.26 MPa) exceeded both the balanced (M2: 4.14 MPa) and polypropylene-dominant mix (M3: 4.03 MPa). The same trend was observed at 0.5%, where M4 (4.52 MPa) outperformed M5 (4.39 MPa) and M6 (4.32 MPa), and at 0.75%, where the basalt-rich mix M7 achieved the highest value of 4.63 MPa, compared to 4.49 MPa (M8) and 4.18 MPa (M9).

This consistent pattern indicates that basalt-rich combinations provide superior peak tensile resistance under splitting loading. The higher stiffness and tensile strength of basalt fibres enhance resistance to crack opening along the diametral failure plane, whereas polypropylene fibres primarily contribute to microcrack control and fibre-matrix interaction. Similar observations regarding the dominant role of basalt fibres in hybrid PP-BF systems have been reported in previous studies [9, 21]

At 1.0% total fibre volume, tensile strength declined for all proportions, particularly in PP-dominant mixes, confirming that excessive fibre interaction reduces reinforcement

efficiency.

Optimum Hybrid Configuration : Based on the 28-day results, the optimum hybrid configuration is identified as 0.75% total fibre volume with basalt-dominant proportion (M7), achieving a splitting tensile strength of 4.63 MPa, representing nearly a 30% improvement over the control concrete. This combination provides the most effective balance between fibre stiffness, dispersion, and matrix continuity, thereby maximizing indirect tensile resistance.

Overall, the results demonstrate that splitting tensile performance in PP-BF hybrid concrete is governed by both total fibre volume and fibre proportion, with basalt-rich intermediate fibre dosages delivering the most efficient tensile reinforcement.

3.4. Water Absorption

Water absorption is a critical durability parameter that reflects pore connectivity, capillary continuity, and resistance to fluid ingress within the cementitious matrix. The 28-day water absorption values of polypropylene-basalt (PP-BF) hybrid fibre-reinforced concrete are presented in Table 5 and illustrated in Figure 5.

Table 5. Water Absorption of PP-BF Hybrid Fibre-Reinforced Concrete (28 Days).

Mix ID	Total Fibre Volume (%)	PP Fibre Volume (%)	Basalt Fibre Volume (%)	Water Absorption (%)
Control	0.00	0.00	0.00	1.96
M1	0.25	0.07	0.18	2.05
M2	0.25	0.125	0.125	2.08
M3	0.25	0.18	0.07	2.14
M4	0.50	0.125	0.375	1.58
M5	0.50	0.250	0.250	1.67
M6	0.50	0.375	0.125	1.83
M7	0.75	0.19	0.56	1.35
M8	0.75	0.375	0.375	1.39
M9	0.75	0.56	0.19	1.53
M10	1.00	0.25	0.75	1.07
M11	1.00	0.50	0.50	1.22
M12	1.00	0.75	0.25	1.29

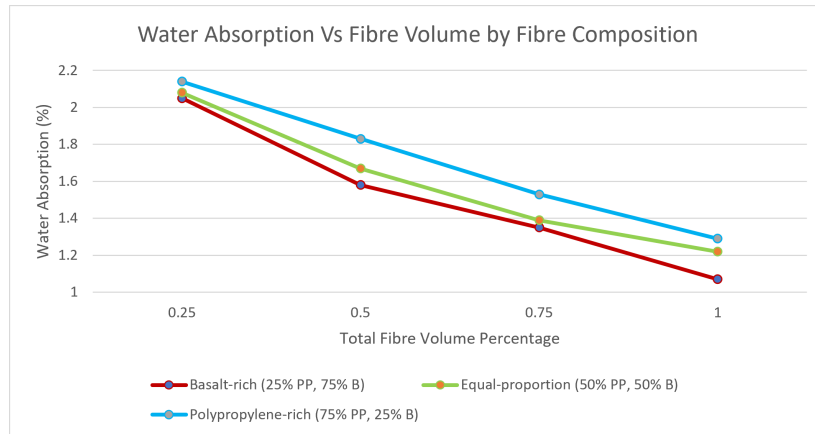


Figure 5. Variation of water absorption with total fibre volume at different PP:BF ratios.

The control mix exhibited a water absorption of 1.96%. At a total fibre volume of 0.25%, absorption marginally increased to 2.05-2.14%, corresponding to a maximum increase of approximately 9% compared to plain concrete. This slight rise indicates that at very low fibre dosages, the fibre-matrix interface may introduce localized discontinuities without sufficiently modifying the capillary network. Similar behaviour has been reported in fibre-reinforced cementitious systems where sub-threshold fibre contents did not significantly reduce permeability-related properties.

With increasing total fibre volume, water absorption decreased substantially. At 0.50% fibre content, absorption reduced to 1.58-1.83%, representing up to a 19% reduction relative to the control mix. The reduction became more pronounced at 0.75%, where values decreased to 1.35% in basalt-dominant systems, corresponding to a 31% decrease. The minimum absorption was recorded at 1.0% total fibre volume, where the basalt-rich mix achieved 1.07%, reflecting a 45% reduction compared to plain concrete. Balanced and polypropylene-rich mixes at the same fibre volume exhibited absorption values of 1.22% and 1.29%, respectively, indicating that the improvement remained significant across all hybrid combinations.

The progressive reduction in water absorption confirms the existence of a threshold fibre volume, approximately between 0.50% and 0.75%, beyond which the hybrid system effectively disrupts capillary continuity. Basalt fibres are known to refine pore structure by decreasing average pore diameter and increasing pore surface complexity, thereby enhancing resistance to fluid transport (Li et al., 2020). Even when total porosity may not decrease substantially, refinement of pore size distribution and increased tortuosity of transport pathways can significantly reduce permeability-related parameters.

The influence of fibre proportion further clarifies the governing mechanism. At every total fibre volume, basalt-rich mixes consistently exhibited lower water absorption than polypropylene-rich mixes. For instance, at 0.50% total fibre volume, absorption increased from 1.58% in basalt-dominant mixes to 1.83% in polypropylene-dominant mixes. A similar trend was observed at 0.75% and 1.0%. This

behaviour highlights the dominant role of basalt fibres in modifying the pore network. Due to their higher stiffness and stronger fibre-matrix interaction, basalt fibres contribute to improved interfacial transition zone compactness and restrict the formation of interconnected capillary pores. Enhanced durability performance of basalt fibre systems has been similarly attributed to pore refinement and improved matrix integrity.

In contrast, polypropylene fibres primarily contribute to micro-crack control and shrinkage mitigation rather than intrinsic pore densification. While polypropylene inclusion can reduce secondary permeability by limiting crack propagation, its effect on capillary pore refinement is comparatively limited. Consequently, polypropylene-rich systems in the present study consistently exhibited slightly higher absorption values than basalt-rich hybrids at equivalent total fibre volumes.

Overall, the results demonstrate that water absorption is governed not merely by total porosity but by pore connectivity and distribution. Within the investigated range, optimum durability performance with respect to water absorption is achieved at total fibre volumes between 0.75% and 1.0%, particularly in basalt-dominant or balanced hybrid systems, where pore refinement effects outweigh any localized interface-induced voids.

4. Conclusion

This study evaluated the mechanical, durability, and microstructural performance of polypropylene-basalt (PP-BF) hybrid fibre-reinforced concrete incorporating total fibre volumes between 0.25% and 1.0% with varying fibre proportions. Based on the experimental results and mechanistic interpretation, the following conclusions are established:

Compressive strength is governed by optimal fibre dosage rather than fibre presence alone. Hybrid fibre incorporation did not produce monotonic strength enhancement. Maximum compressive efficiency was achieved at low to moderate total fibre volumes (0.25-0.50%), particularly in basalt-rich

combinations. At higher dosages, reductions in compressive strength were associated with fibre interaction effects and dispersion limitations, indicating that matrix continuity remains critical for compressive load transfer.

Hybridisation significantly enhances deformation capacity under compression. Although peak compressive strength showed limited improvement, strain capacity increased consistently with fibre addition. Basalt fibres contributed to improved pre-peak stiffness and crack delay, whereas polypropylene fibres enhanced post-peak ductility through crack bridging and pull-out mechanisms. The hybrid system therefore promotes a transition from brittle to ductile compressive behaviour.

Flexural performance benefits substantially from complementary fibre action. All hybrid mixes demonstrated improved flexural strength relative to plain concrete, with superior performance observed in basalt-dominant and balanced combinations at higher fibre volumes (0.75-1.0%). Basalt fibres primarily governed crack initiation resistance and peak load capacity, while polypropylene fibres sustained post-cracking deformation, resulting in enhanced toughness and energy absorption.

Splitting tensile strength exhibits an optimum hybrid range. Tensile resistance increased up to a total fibre volume of 0.75%, beyond which marginal reductions were observed. This indicates that tensile performance depends on effective fibre dispersion and stress-transfer efficiency. Basalt-rich combinations consistently achieved higher peak tensile capacity due to their higher stiffness and crack-bridging effectiveness.

Durability performance improves within the investigated fibre range. Water absorption decreased progressively with increasing fibre content, with the lowest values recorded at 1.0% total fibre volume. Basalt fibres contributed predominantly to pore refinement and interfacial transition zone densification, while polypropylene fibres assisted in microcrack control and capillary discontinuity.

Overall, polypropylene-basalt hybridisation provides a rational approach to achieving balanced improvements in strength, ductility, and durability. For structural applications prioritising compressive efficiency, total fibre volumes of 0.25-0.50% are recommended. Where enhanced crack control and durability are critical, hybrid fibre volumes of 0.75-1.0%, particularly basalt-rich or balanced combinations, offer superior overall performance.

Abbreviations

BF	Basalt Fibre
PP	Polypropylene
PP-BF	Polypropylene-Basalt Fibre
HFRC	Hybrid Fibre-Reinforced Concrete
GPa	Gigapascal
MPa	Megapascal
ITZ	Interfacial Transition Zone
OPC	Ordinary Portland Cement

M40	M40 Grade Concrete
W/B	Water-to-Binder Ratio
IS	Indian Standard

Author Contributions

Ram Bhupal Reddy Anna Reddy: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing

Jayarami Reddy Bommi Reddy: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Ashteyat, A., Obaidat, A. T., Qerba'a, R., and Abdel-Jaber, M., Influence of basalt fiber on the rheological and mechanical properties and durability behavior of self-compacting concrete (SCC), *Fibers*, vol. 12, no. 7, Article no. 52, June, 2024. <https://doi.org/10.3390/fib12070052>
- [2] Cakiroglu, C., Aydın, Y., Bekdaş, G., and Geem, Z. W., Interpretable predictive modelling of basalt fiber reinforced concrete splitting tensile strength using ensemble machine learning methods and SHAP approach, *Materials*, vol. 16, no. 13, Article no. 4578, June, 2023. <https://doi.org/10.3390/ma16134578>
- [3] Chia, E., et al., Performance of hybrid basalt-recycled polypropylene fibre-reinforced concrete, *Structures*, vol. 75, Article no. 108711, 2025. <https://doi.org/10.1016/j.jstruc.2025.108711>
- [4] Del Savio, A. A., Esquivel, D. L. T., de Andrade Silva, F., and Agreda Pastor, J., Influence of synthetic fibers on the flexural properties of concrete: prediction of toughness as a function of volume, slenderness ratio and elastic modulus of fibers, *Polymers*, vol. 15, Article no. 909, February, 2023. <https://doi.org/10.3390/polym15040909>
- [5] Deng, Z., Liu, X., Liang, N., de la Fuente, A., and Peng, H., Flexural performance of a new hybrid basalt-polypropylene fiber-reinforced concrete oriented to concrete pipelines, *Fibers*, vol. 9, no. 7, Article no. 43, July, 2021. <https://doi.org/10.3390/fib9070043>
- [6] Ding, L., Lin, Z., Xu, C., Xu, H., Li, B., and Shen, J., Study on the hybrid effect of basalt and polypropylene fibers on the mechanical properties of concrete, *Buildings*, vol. 15, no. 17, Article no. 3197, September, 2025. <https://doi.org/10.3390/buildings15173197>

- [7] Fu, Q., Bu, M., Su, L., Liu, L., Chen, L., Li, N., and Niu, D., Triaxial mechanical behaviour of hybrid basalt-polypropylene fibre-reinforced concrete: the effect of micro-fibres at multi-scale levels, *Materials and Structures*, vol. 54, no. 3, Article no. 126, May, 2021. <https://doi.org/10.1617/s11527-021-01723-9>
- [8] Fu, Q., Zhang, Z., Xu, W., Zhao, X., Zhang, L., Wang, Y., and Niu, D., Flexural behavior and prediction model of basalt fiber/polypropylene fiber-reinforced concrete, *International Journal of Concrete Structures and Materials*, vol. 16, no. 1, Article no. 31, April, 2022. <https://doi.org/10.1186/s40069-022-00524-w>
- [9] Hu, X., Guo, Y., Lv, J., and Mao, J., The mechanical properties and chloride resistance of concrete reinforced with hybrid polypropylene and basalt fibres, *Materials*, vol. 12, no. 15, Article no. 2371, July, 2019. <https://doi.org/10.3390/ma12152371>
- [10] Li, Y., Shen, A., and Wu, H., Fractal dimension of basalt fiber reinforced concrete and its correlations to pore structure, strength and shrinkage, *Materials*, vol. 13, no. 14, Article no. 3238, July, 2020. <https://doi.org/10.3390/ma13143238>
- [11] Liu, M., Dai, W., Zhong, C., and Yang, X., Study on mechanical properties and microstructure of basalt fiber reactive powder concrete, *Buildings*, vol. 12, no. 10, Article no. 1734, October, 2022. <https://doi.org/10.3390/buildings12101734>
- [12] Mohanty, S. K., Pandit, N. K., Sah, P. K., Mahaseth, N., Yadav, R., Biswal, D. R., Mohapatra, B. G., Beriha, B., Pradhan, R., and Pradhan, S. K., Durability, capillary rise and water absorption properties of a fiber-reinforced cement-stabilized fly ash-stone dust mixture, *Infrastructures*, vol. 9, no. 2, Article no. 17, January, 2024. <https://doi.org/10.3390/infrastructures9020017>
- [13] Selvan, K., Ismail, A. A. M., and Rathinavel, N., Synergistic fiber hybridization: unlocking superior mechanical performance in cementitious composites, *Discover Civil Engineering*, vol. 1, no. 1, Article no. 113, November, 2024. <https://doi.org/10.1007/s44290-024-00129-0>
- [14] Tan, Y., Ma, C., Zhao, B., Xiong, W., Chen, X., and Yu, J., Study and microanalysis on the effect of the addition of polypropylene fibres on the bending strength and carbonization resistance of manufactured sand concrete, *Polymers*, vol. 15, no. 9, Article no. 2139, April, 2023. <https://doi.org/10.3390/polym15092139>
- [15] Vatin, N. I., Hematibahar, M., and Gebre, T. H., Impact of basalt fiber reinforced concrete in protected buildings: a review, *Frontiers in Built Environment*, vol. 10, no. 1, Article no. 1407327, May, 2024. <https://doi.org/10.3389/fbuil.2024.1407327>
- [16] Wu, H., Qin, X., Huang, X., and Kaewunruen, S., Engineering, mechanical and dynamic properties of basalt fiber reinforced concrete, *Materials*, vol. 16, no. 2, Article no. 623, January, 2023. <https://doi.org/10.3390/ma16020623>
- [17] Wu, J., Pang, Q., Lv, Y., Zhang, J., and Gao, S., Research on the mechanical and physical properties of basalt fiber-reinforced pervious concrete, *Materials*, vol. 15, no. 19, Article no. 6527, September, 2022. <https://doi.org/10.3390/ma15196527>
- [18] Xue, Z., Qi, P., Yan, Z., Pei, Q., Zhong, J., and Zhan, Q., Mechanical properties and crack resistance of basalt fiber self-compacting high strength concrete: an experimental study, *Materials*, vol. 16, Article no. 4374, June, 2023. <https://doi.org/10.3390/ma16124374>
- [19] Xu, L., Li, B., Ding, X., Chi, Y., Li, C., Huang, B., and Shi, Y., Experimental investigation on damage behavior of polypropylene fiber reinforced concrete under compression, *International Journal of Concrete Structures and Materials*, vol. 12, no. 1, Article no. 68, July, 2018. <https://doi.org/10.1186/s40069-018-0302-3>
- [20] Yang, Y., Xin, C., Sun, Y., Di, J., and Liang, P., Experimental study on the mechanical properties of hybrid basalt-polypropylene fibre-reinforced gangue concrete, *Applied Sciences*, vol. 14, no. 1, Article no. 453, January, 2024. <https://doi.org/10.3390/app14010453>
- [21] Zeng, H., Zhang, J., Li, Y., Su, X., Gu, C., and Zhang, K., Mechanical properties and microstructure of basalt fiber reinforced concrete under the single-side salt-freezing-drying-wetting cycles, *International Journal of Concrete Structures and Materials*, vol. 16, Article no. 44, May, 2022. <https://doi.org/10.1186/s40069-022-00535-7>
- [22] Zeng, W., Wang, W., Wang, Q., Li, M., Zhang, L., and Tong, Y., Influence of polypropylene fiber on concrete permeability under freeze-thaw conditions and mechanical loading, *Materials*, vol. 17, no. 12, Article no. 2945, June, 2024. <https://doi.org/10.3390/ma17122945>
- [23] Zhou, H., Jia, B., Huang, H., and Mou, Y., Experimental study on basic mechanical properties of basalt fiber reinforced concrete, *Materials*, vol. 13, no. 6, Article no. 1362, March, 2020. <https://doi.org/10.3390/ma13061362>
- [24] Zhu, H., Wen, S., Li, X., Li, Y., and Fu, Z., Damage evolution of polypropylene-basalt hybrid fiber ceramsite concrete under chloride erosion and dry-wet cycle, *Polymers*, vol. 15, no. 20, Article no. 4179, October, 2023. <https://doi.org/10.3390/polym15204179>