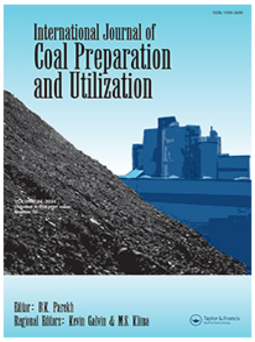

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Enhancing concrete beam performance with PVA fibers, coal ash, and graphene fabric: a comprehensive structural analysis

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ABSTRACT

This study evaluates the structural performance of Polyvinyl Alcohol Cementitious Composites (PVCC)-layered reinforced concrete beams with coal ash under static loading. Experimental investigations included first crack load, ultimate load, load-deflection behavior, ductility, stiffness, and energy absorption. Results highlight the influence of Polyvinyl Alcohol-(PVA) fiber dosage on structural behavior. The control specimen exhibited an initial crack load of 80kN, with subsequent specimens showing varied crack initiation loads influenced by PVA fiber content. Optimal performance was observed at 1.2% PVA fiber dosage, with higher dosages leading to earlier crack initiation. Ultimate load carrying capacity increased with PVA fiber addition, reaching a peak at 1.2% dosage before slight decreases occurred with higher dosages. Load-deflection behavior demonstrated the superior performance of PVCC layered beams, particularly specimen BP3, attributed to optimal fiber content. Ductility, stiffness, and energy absorption increased with PVA fiber reinforcement, with 1.2% dosage yielding optimal results. Excessive fiber content led to diminishing returns. Energy index analysis revealed superior energy dissipation in specimens with higher PVA fiber content, emphasizing the effectiveness of fiber reinforcement in enhancing structural performance. Overall, the study underscores the importance of optimizing PVA fiber dosage to maximize structural resilience and load-bearing capacity in PVCC-layered concrete beams with coal ash.

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KEYWORDS
PVCC layered beams; concrete beam; coal ash; ductility

Introduction

In modern construction practices, the quest for innovative materials and techniques to enhance the structural performance of reinforced concrete beams remains a key focus (Parghi and Alam 2018). Particularly, the incorporation of Polyvinyl Alcohol (PVA) fiber and coal ash in concrete mixtures has garnered attention for their potential to improve the mechanical properties and durability of reinforced concrete structures (Sadrmomtazi, Khabaznia, and Tahmouresi 2016; Aljarrah and Abdelal 2019). This study investigates the structural behavior of Polyvinyl Alcohol Cementitious Composites (PVCC)-layered reinforced concrete beams with coal ash under static loading conditions. The utilization of Grade 53 Ordinary Portland Cement (OPC) conforming to IS 12,269–1987 standards and

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coal ash from the Mettur Thermal Power Station, Tamilnadu, forms the basis of the experimental investigation. The experimental setup involves casting test specimens to examine the structural behavior of both PVCC-layered and graphene fiber fabric-wrapped reinforced concrete beams, adhering to relevant Indian standards and design codes. The evaluation encompasses various parameters including first crack load, ultimate load-carrying capacity, load-deflection behavior, ductility, stiffness, energy absorption, and energy index. These parameters provide comprehensive insights into the influence of PVA fiber dosage on the structural integrity and load-bearing capacity of PVCC-layered reinforced concrete beams with coal ash (Loganathan et al. 2022; Meng et al. 2017). Through systematic experimentation and analysis, this study aims to contribute to the understanding of the effectiveness of PVA fiber reinforcement in enhancing the structural performance of reinforced concrete beams, with implications for optimizing fiber dosage in practical engineering applications (Yong Kim, Kong, and Li 2003). The findings are expected to inform future advancements in construction materials and techniques aimed at achieving more resilient and sustainable infrastructure. This research addresses the need to enhance the structural performance of reinforced concrete beams using sustainable materials (Shanmugasundaram et al. 2022). Conventional concrete lacks sufficient ductility, stiffness, and energy absorption, critical for structural integrity under dynamic stresses like seismic loading. The study explores incorporating polyvinyl alcohol (PVA) fibers and coal ash in concrete mix designs, aiming to optimize fiber dosage to maximize load-bearing capacity, deflection resistance, and robustness (Z. B. Wang et al. 2021). Additionally, it evaluates PVCC nano layering and basalt fiber fabric wrapping as innovative reinforcement techniques. By systematically investigating these methods, the research aims to inform better design practices, contributing to more resilient and sustainable construction materials and structures.

Tara & Jagannatha (Sen and Reddy 2011) reported that the materials chosen for structural upgradation must, in addition to functional efficiency and increasing or improving the various properties of the structures, fulfill some criterion, for the cause of sustainability and better quality (Praveen Kumar 2019). Domke et al. (2011) have reported that considerable efforts have been taken worldwide to utilize local natural waste and by-product materials as supplementary cementing materials to improve the properties of cement concrete. Lepech and Li (2009) deal with the importance of sustainability of the environment in which the structure is being built in making infrastructure design and maintenance decisions. A preliminary case study is being done on the green material design framework (Haincová and Hájková 2020). To improve the sustainability of the structure, a new cement-based composite is required, and it is being analyzed by application in the green material design framework (Padmapoorani, Senthilkumar, and Mohanraj 2023). A large number of substitutes including industrial wastes were used to gauge their properties with ECC. Among them, green foundry sand, fly ash, and cement kiln dust show a greater tendency to replace certain raw materials within ECC composites (Karbhari, Wang, and Gao 2001). The addition of green foundry sand reduces the tensile strain capacity of ECC. By Re-engineering the fiber-matrix interface, the multiple cracking behavior and strain hardening capacity is being restored. The result of this paper indicates the application of Micromechanics and sustainable infrastructure design performance. Ahmed, Hirozomihashi, and Mihashi (2011) discuss the various properties of PVA fiber-reinforced cementitious composites. The test is being done for different hybrids of PVA fibers of varying lengths. Ibrahim et al. (2022), Kendall, Keoleianand Michael D Lepech, and Lepech (2008), Saleh et al. (2022) deal with the study of wet mixtures suitable for the shotcreting process in the fresh state. This can be developed by creating micromechanics and rheological designs. Due to the controlled rheology of the fiber matrix and dispersion of fibers, the spray ability and pumpability of ECC are enabled (Gupta and Verma 2016). The result shows that an ECC having pump ability and spray ability properties at fresh and strain-hardened states has been developed by rheological and micromechanical design (Z. Wang, Wang, and Zhu 2022; Zong et al. 2020; Raju and Dharmar 2016). In India, thermal power plants produce over 117 million tons of coal ash annually, posing environmental threats. Utilizing ash in construction, particularly in brick-making, offers a greener alternative and reduces soil excavation. Muhammed, Thangaraju, and Shanmugamoorthy (2023) investigate the viability of using fly ash-based artificial coarse aggregate (FACA) in concrete production, comparing its durability with conventional concrete across various grades (M20, M25, M30). Nanjappan et al. (2024) compared the flexural strength of traditional concrete beams with those modified using kaolinite coal. Eighteen samples of each type were tested using flexural strength equipment. Statistical analysis, including Levene's test and t-tests, revealed a highly significant difference in mean flexural strength between the two groups ($p = .000$). A case study evaluated the production cost and CO_2 emissions of concrete incorporating coal bottom ash as a fine aggregate (Velumani et al. 2023). Results showed significant impacts from ash treatment processes and the availability of subsidies. Saravanakumar et al. (2024) study investigates the macro and micro properties of bottom ash geopolymer concrete (BAGPC) under aggressive environmental exposures. BAGPC, utilizing sodium silicate and sodium hydroxide as activators, demonstrated superior durability and bonding compared to conventional concrete. Microstructure analysis confirms its potential for widespread application in the construction industry. Golewski (2023) investigated the relationship between water absorption and compressive strength in concretes containing coal fly ash (CFA) at 0%, 20%, and 30% levels. Results showed that strength and absorption depended on CFA content, cement matrix structure, and interfacial transition zone (Raj and Rao 2023). 20% CFA increased strength with higher absorption, while 30% CFA decreased both, suggesting potential durability benefits for submerged structures (Ghosal 2023; Khan, Zhang, and Lee 2021; Mpalaskas, Aggelis, and Matikas 2021) study investigates fracture restoration in fiber reinforced concrete beams using acoustic emission (AE) techniques. Three types of metal fibers were tested in four-point bending, repaired with epoxy resin, and reloaded, with AE parameters revealing microstructure insights and restoration levels. Thomoglou et al. (2022) study evaluates the impact of various surfactants on carbon fiber (CF) distribution in carbon fiber reinforced cement-based composites (CFRC) concerning mechanical properties and strain-sensing ability. Three surfactants were tested with wet and dry mixing methods. Results showed significant improvements in flexural strength, modulus of elasticity, and stress-sensing ability, recommending dry mixing for economical and effective structural health monitoring systems. Che et al. (2022) study investigates replacing river sand with desert sand in Desert-Sand-based steel-PVA hybrid Fiber Reinforced ECC (H-DSECC). Using high-volume fly ash, steel, and PVA fibers, results show optimal properties with 40% desert sand, achieving a tensile strain capacity of 1.467%, tensile strength of 7.5 MPa, and compressive strength of 41.03 MPa. Thomoglou et al. (2023) research explores hybrid cement-mortar composites with multi-walled carbon nanotubes (MWCNTs), carbon fibers (CFs), and polypropylene microfibers

(PPs). Optimal nano- and micro-reinforcement (0.2 wt% MWCNTs and 0.5 wt% CFs) significantly improved flexural strength, toughness, conductivity, and piezoresistive response, demonstrating exceptional mechanical and electromechanical performance, and enhanced strain-sensing ability, highlighting the superiority of the hybrid-reinforced mortar. Lee, Lee, and Yoo (2023) study conducted pull-out tests to examine the bond behavior of rebar in PVA fiber and CNT cementitious composites. Results showed bond strength increased with smaller rebar diameters or higher CNT mix ratios, leading to a new predictive model. Naoum et al. (2023) study investigates synthetic macro-fibers in fiber-reinforced concrete (FRC) prisms and their flexural response using a novel structural health monitoring (SHM) system with PZT-enabled electromechanical impedance (EMI) techniques for real-time damage detection under seismic loading simulations. Liu et al. (2024) study investigates polyvinyl alcohol fiber recycled aggregate concrete (PVA-FRAC) under cyclic loading. Results show that PVA fiber and optimal recycled aggregate ratios improve ductility and energy dissipation. The best performance is achieved with 0.10% PVA fiber, increasing energy dissipation by 26.19%. A damage constitutive model for PVA-FRAC is proposed, aiding engineering applications and regulation revisions (Kumar et al. 2021). The presented study suggests that incorporating PVA fibers in recycled aggregate concrete can significantly improve the material's ductility and energy dissipation capacity. This has the potential to impact the construction industry by promoting more sustainable and resilient building materials (Meena, Singh, and Singh 2024). However, the limitations of using PVA fibers, such as potential cost implications and performance variability with different aggregate types, should be considered. Further research and practical assessments are needed to fully understand the long-term effects and feasibility of widespread implementation in structural elements.

The significance and novelty of this work lie in its comprehensive evaluation of how Polyvinyl Alcohol (PVA) fibers and graphene fiber fabric enhance the mechanical properties of M30-grade concrete beams. By incorporating these materials, the study significantly improves compressive strength, stiffness, ductility, and energy absorption, making the concrete more suitable for high-performance structural applications. Notably, the research identifies the optimal dosage of PVA fibers (1.2%), maximizing mechanical properties and offering practical insights for construction, especially in seismic zones or infrastructure requiring long-term durability. Utilizing coal ash as a supplementary material also promotes sustainability by recycling industrial by-products, reducing environmental impact. The innovative combination of PVA fibers and graphene fiber fabric, along with the novel layered approach of applying PVCC at the cover zone and wrapping beams, curbs tension cracks and enhances shear resistance, demonstrating significant improvements in structural integrity. Also, a new wrapping technique using natural-based graphene fiber fabric was used in this work to strengthen the beams. This natural-based graphene fiber fabric was bonded externally by epoxy resin at the bottom alone and bottom with side faces of the beam up to the neutral axis. The study's comprehensive testing and analysis provide a comprehensive understanding of the impact of polymer and graphene enhancements over different curing periods, revealing a complex understanding of fiber dosage effects.

Materials and Sample Preparation

The study utilized Grade 53 Ordinary Portland Cement (OPC) conforming to IS 12,269–2013 standards, with testing conducted according to IS: 4031 (S. Kumar et al. 2016) due to its superior early strength and enhanced durability. Coal ash (80 µm particle size) collected from Mettur Thermal Power Station, Tamilnadu, was employed to provide additional fines for compaction (Pan et al. 2015). River sand passing through 4.75 mm and retained on 600 µm sieve was used for specimen casting, while sand passing through 4.75 mm and retained on 200 µm sieve was utilized for Polyvinyl Alcohol Cementitious Composites (specific gravity: 2.70). Crushed blue granite coarse aggregates (particle size: 20 mm, specific gravity: 2.68) adhered to IS 383–2016 standards (Mohanraj, Senthilkumar, and Padmapoorani 2022). Polyvinyl Alcohol Cementitious Composites (PVCC) were developed and it is provided at the bottom of the beam at the cover zone (runs across the specimen) instead of cover thickness with various dosage levels of Polyvinyl Alcohol (PVA) fiber addition (Amusan 2024; Ankur and Singh 2024b; Sun et al. 2018; Kim et al. 2023). Tap water was used for mixing and curing. Polyvinyl Alcohol fiber was procured from Spinning King Limited, Gujarat, while 320 grams per meter square graphene fiber fabric was acquired from Arrow Textile Technical Limited, Mumbai. The properties of PVA fiber are given in Table 1. The Structural detailing of the concrete beam including reinforcement detailing, length, width, and depth of the beam is given in Figure 1.

Table 1. Properties of PVA fiber.

Elongation (%)	Young's modulus (GPa)	Nominal strength (MPa)	Diameter (µm)	Length (mm)
6	41.5	1510	7	10

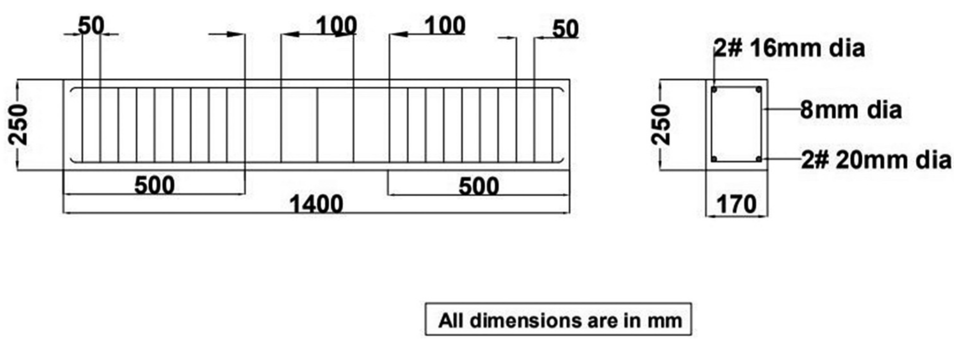

Figure 1. Structural drawing of concrete beam.

Table 2. Properties of graphene fiber fabric.

Sl. No.	Properties	Values
1	Diameter (mm)	0.010
2	Tensile strength (MPa)	4125

Table 3. Mix details for one cubic meter.

Sl.No.	Mix ID of Beam	Volume of fiber (%)	Materials (kg)					
			Cement	Fine Aggregate	Coal Ash	Water	Superplasticizer	PVA Fibre
1	B0	–	558	446	669	324	–	–
2	BP1	0.4	558	446	669	324	6.7	8.01
3	BP2	0.8	558	446	669	324	6.7	16.02
4	BP3	1.2	558	446	669	324	6.7	24.04
5	BP4	1.6	558	446	669	324	6.7	32.05
6	BP5	2.0	558	446	669	324	6.7	40.07

A single layer of Graphene fiber fabric was formed by melting at a high temperature (1450°C) and rapidly drawn into a continuous fiber, and it was made as fabric. It is commonly known as Graphene Fiber Fabric (Ankur and Singh 2024b). The properties of Graphene fiber fabric are shown in Table 2.

Mix Design of Concrete Beam and Specimen Details

M30-grade concrete beams have been prepared, and six samples have been prepared as specified in Table 3. B0 indicates conventional concrete beam and BP1 to BP5 indicates modified concrete beam.

Experimental Study

Six test specimens were cast to examine the structural behavior of PVCC layered and graphene fiber fabric-wrapped reinforced concrete beams. Design adhered to IS 456:2000, detailing per IS 13,920:2016. Curing lasted 28 days, employing plywood sheet molds. PVCC layering at the cover zone aimed to curb tension cracks, while graphene fiber fabric wrapping targeted tension and shear crack mitigation. Tension and compression reinforcements included 20 mm and 16 mm diameter bars. Transverse reinforcement consisted of 8 mm diameter bars spaced at 50 mm c/c from both ends and 100 mm c/c elsewhere (Zhang et al. 2024; Mamadaliyev and Fazilov 2024). Fabrication involved concrete mixing with a mixer and casting in plywood sheet molds.

Test Results and Discussion

This section evaluates PVCC-layered reinforced concrete beams with coal ash under static loading. Two parts cover structural behavior: PVCC-layered beams and graphene fiber fabric-wrapped beams. Flexural failure was observed. Parameters including first crack load, ultimate load, load-deflection, ductility, stiffness, energy absorption, and energy index are analyzed. Figure 2 represents the experimental test setup and beam failure pattern.

Table 4. Compressive strength of PVCC concrete specimens.

Sl.No.	Mix ID of Beam	Compressive strength (MPa)			
		7 days	14 days	28 days	56 days
1	B0	19.21	27.00	30.10	34.31
2	BP1	21.35	29.11	32.06	36.60
3	BP2	22.98	30.94	33.15	37.48
4	BP3	24.53	32.07	35.27	39.67
5	BP4	26.61	34.82	36.93	40.19
6	BP5	29.22	35.76	37.90	41.07

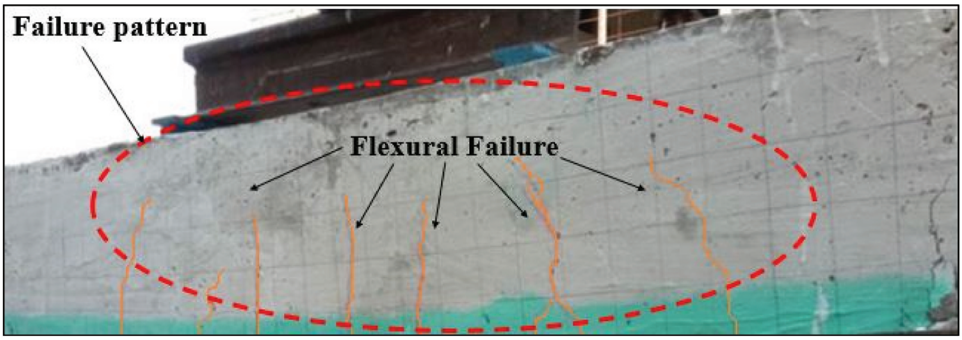

Figure 2. Experimental setup and failure pattern of beam specimen.

Compressive Strength

M30 grade concrete beams were prepared, and six samples were prepared with varying mix IDs. The test results of all the specimens were shown in Table 4. For Beam B0, the compressive strengths recorded were 19.21 MPa at 7 days, 27.00 MPa at 14 days, 30.10 MPa at 28 days, and 34.31 MPa at 56 days. Beam BP1 exhibited compressive strengths of 21.35 MPa at 7 days, 29.11 MPa at 14 days, 32.06 MPa at 28 days, and 36.60 MPa at 56 days. For Beam BP2, the compressive strengths were 22.98 MPa at 7 days, 30.94 MPa at 14 days, 33.15 MPa at 28 days, and 37.48 MPa at 56 days. Beam BP3 showed compressive strengths of 24.53 MPa at 7 days, 32.07 MPa at 14 days, 35.27 MPa at 28 days, and 39.67 MPa at 56 days. Beam BP4 had compressive strengths of 26.61 MPa at 7 days, 34.82 MPa at 14 days, 36.93 MPa at 28 days, and 40.19 MPa at 56 days. Finally, Beam BP5 demonstrated compressive strengths of 29.22 MPa at 7 days, 35.76 MPa at 14 days, 37.90 MPa at 28 days, and 41.07 MPa at 56 days. These data reflect the progressive increase in compressive strength over time for each beam mix.

From Figure 3, the initial compressive strength of the samples ranges from 19.21 MPa for B0 to 29.22 MPa for BP5. The significant increase in early strength with the addition of polymers (as indicated by the increasing mix IDs) suggests that the modified mixes (BP1 to BP5) exhibit superior early-age strength compared to the control mix (B0). This improvement can be attributed to the enhanced hydration process and early formation of a denser microstructure due to the additives. By 14 days, the compressive strength continues to rise, with values ranging from 27.00 MPa for B0 to 35.76 MPa for BP5. The pattern of increasing strength with higher mix IDs remains consistent, indicating that the additives continue to positively influence the hydration process and the microstructure development. At 28 days, the typical maturity period for concrete, the strengths range from 30.10 MPa for B0 to 37.90 MPa for BP5. The data show that the enhanced mixes (BP1 to BP5) not only meet but exceed the expected strength for M30-grade concrete. The additives likely contribute to a more refined and continuous pore structure, reducing porosity and increasing density. Long-term strength data show values from 34.31 MPa for B0 to 41.07 MPa for BP5. The continued increase in strength at 56 days for all samples indicates ongoing hydration and pozzolanic reactions, especially in mixes containing supplementary materials. The long-term strength

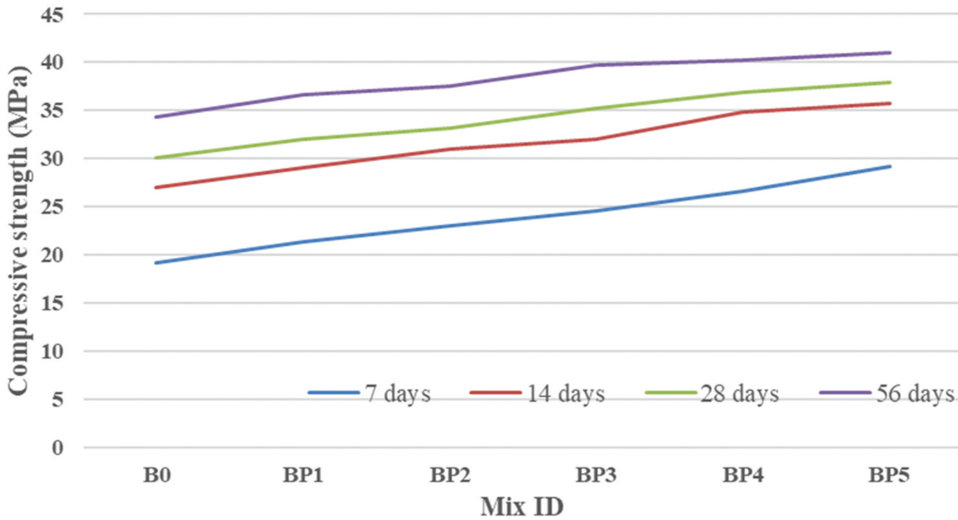

Figure 3. Compressive strength of PVCC specimens.

gain is essential for ensuring durability and structural integrity over the life span of the concrete structure. The control mix shows a steady increase in strength, typical of conventional concrete. However, it exhibits the lowest strength values at all stages, indicating room for improvement with additives. The addition of polymers in BP1 to BP5 results in a significant improvement in compressive strength across all curing periods. The increasing strength with higher mix IDs suggests that the proportion of additives correlates positively with strength enhancement. BP5, the mix with the highest polymer content, shows the highest strength at all ages, indicating an optimal formulation for achieving maximum strength. Overall, the data indicate that incorporating specific polymers and additives into the concrete mix significantly enhances both early and long-term compressive strengths, making these modified concretes suitable for applications requiring higher performance and durability.

PVCC Layered Reinforced Concrete Beam with Coal Ash

First Crack Load

The study of the first crack load of PVCC-layered reinforced concrete beams with coal ash (BP1 to BP5) in comparison to a control specimen (B0) indicated unique load thresholds. The control specimen (B0) exhibited an initial crack initiation at 80kN, localized at the bottom face of the beam. Introducing 0.4% PVA fiber into the PVCC layered concrete beam (BP1) shifted the first crack load to 84kN (Figure 4). Subsequent specimens (BP2 and BP3), incorporating 0.8% and 1.2% PVA fiber, demonstrated further increases in the first crack load to 88kN and 92kN, respectively. Conversely, specimens BP4 and BP5, featuring 1.6% and 2% PVA fiber addition, experienced earlier crack initiation, observed at 86kN and 82kN, respectively. Integrating more reactive materials like PVA has proven effective. Coal ash, rich in calcium and other reactive elements, accelerates the polymerization process, facilitating the formation of calcium silicate hydrate (C-S-H) gel alongside the primary aluminosilicate gel. This results in a denser, more cohesive microstructure, reducing setting time and significantly improving the load-carrying capacity of the material. The synergy between fly ash and PVA optimizes the use of both materials, enhancing the environmental and economic benefits of the geopolymer. Consequently, Cai et al. (2022) findings underscore the influence of PVA fiber dosage on the structural behavior and load-bearing capacity of PVCC-layered concrete beams with coal ash.

Ultimate Load Carrying Capacity

The ultimate load-carrying ability of control reinforced concrete beams with coal ash (B0) and PVCC layered reinforced concrete beams with variable PVA fiber content (BP1 - BP5) was assessed, as shown in Figure 4. The control specimen exhibited an ultimate load of 113 kN, reached at 113 kN load level. Upon the addition of 0.4% and 0.8% PVA fiber in PVCC layered beams, the ultimate loads increased to 125kN and 132kN for specimens BP1 and BP2, respectively. Specimen BP3, with 1.2% PVA fiber addition, achieved the highest ultimate load of 141kN. However, specimens BP4 and BP5, featuring 1.6% and 2% PVA fiber addition, experienced slight decreases in ultimate load to 137kN and 122kN, respectively (Mohanraj and Vidhya 2024). The comparison in Figure 5 highlights the first crack and ultimate load differences between control and PVCC layered beams. The optimal dosage of PVA fiber addition was determined to be 1.2%, as beyond this threshold, the cement mortar's integrity may diminish due to increased fiber content, potentially leading to bonding issues and strength reduction.

Load Deflection Behavior

The load-deflection behavior of the control reinforced concrete beam with coal ash (B0) and PVCC layered reinforced concrete rectangular beams (BP1 to BP5) was analyzed, as illustrated in Figure 5. Specimen BP3 exhibited superior load-bearing capacity and deflection resistance attributed to optimal fiber content in the PVCC layered mixtures compared to other specimens.

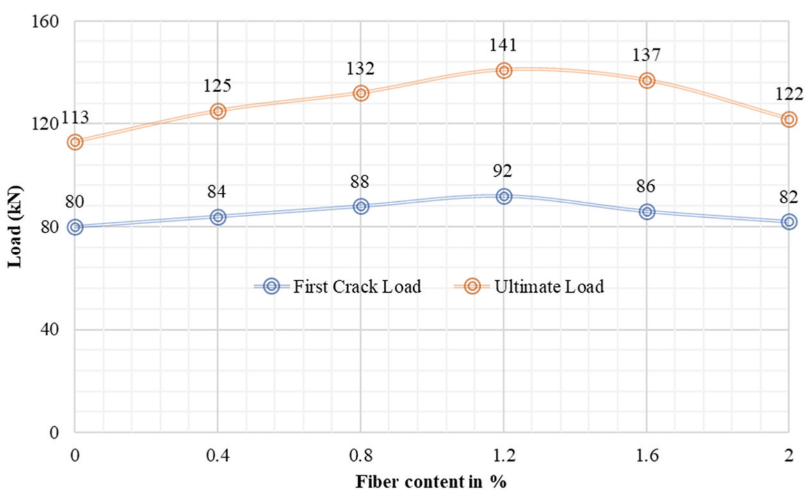

Figure 4. Comparison of first crack load and ultimate load carrying capacity of control and PVCC layered beams.

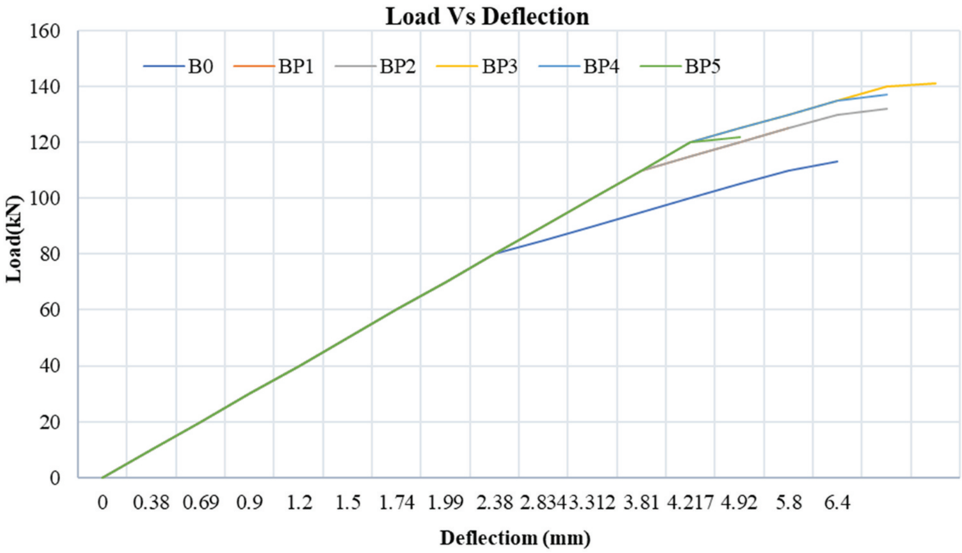

Figure 5. Comparisons between load deflection curves of control and PVCC layered beam.

As the load increased, multiple cracks propagated without beam splitting. A change in the slope of the load-deflection curve was observed upon crack formation and propagation in PVCC layered beam specimens. The first crack was initiated at the beam bottom at 80 kN for control specimen B0, with a corresponding deflection of 2.38 mm (Pattusamy et al. 2023). At 113 kN, B0 reached the ultimate load with a deflection of 6.4 mm. For BP1, the ultimate load was 125 kN with a deflection of 4.44 mm. BP2 exhibited the first crack and ultimate load at 88 kN and 132 kN, with deflections of 1.62 mm and 4.72 mm, respectively. BP3 showed the first crack and ultimate load at 92 kN and 141 kN, with deflections of 1.27 mm and 5.14 mm, respectively. BP4 demonstrated first crack and ultimate load at 86 kN and 137 kN, with deflections of 1.21 mm and 4.52 mm, respectively. BP5 exhibited a first crack at 82 kN with a deflection of 1.88 mm, reaching an ultimate load of 122 kN with a deflection of 4.33 mm. The comparison of load-deflection curves in Figure 6 shows the superior performance of BP1 to BP5 compared to control beam B0. Flexural failure was observed in all specimens (BP0 to BP5).

Ductility Behavior

The control beam specimen (B0) exhibited a ductility value of 2.68. Incorporating 0.4% PVA fiber in the PVCC layered beam specimen (BP1) increased the ductility value by 1.37 times. Similarly, the addition of 0.8% PVA fiber in the PVCC layered beam (BP2) enhanced the ductility value by 1.76 times compared to B0. Notably, the addition of 1.2% PVA fiber in the PVCC layered beam (BP3) yielded a ductility value of 5.90, representing a 2.20 times increment over B0. Although the BP4 and BP5 specimens, with 1.6% and 2% PVA fiber additions respectively, exhibited ductility values of 4.96 and 4.38, which were higher than B0, they were lower than BP3. Figure 6 illustrates the ductility factor values for both control and PVCC layered beams, clearly showing the incremental increases in ductility with the addition of varying percentages of PVA fibers. The highest ductility improvement was

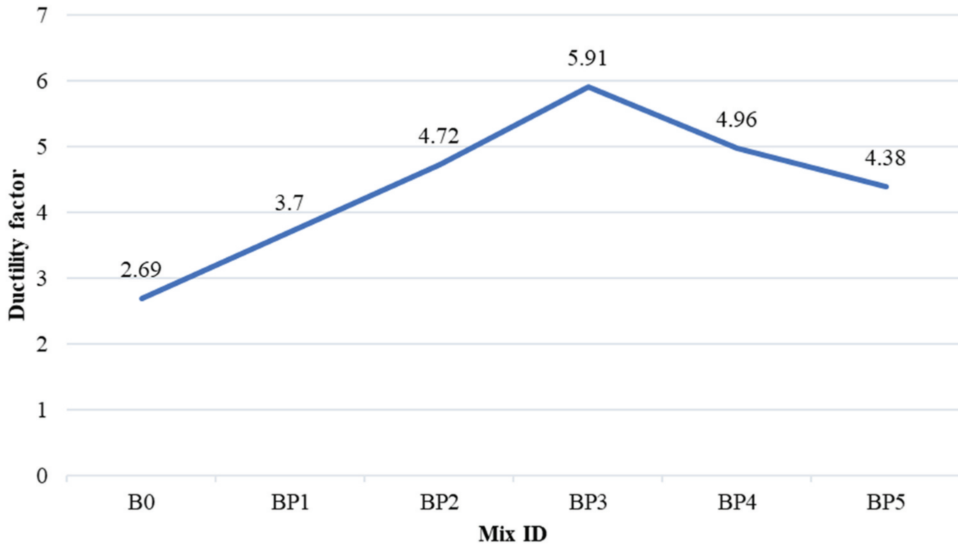

Figure 6. Ductility factor of control and PVCC layered beams.

observed in the BP3 specimen with 1.2% PVA fiber, while further increases in PVA fiber content in BP4 and BP5 did not surpass the ductility value of BP3.

Stiffness

The stiffness of control and PVCC-layered reinforced concrete beams with coal ash was evaluated, revealing notable enhancements with the addition of PVA fibers. The stiffness of the beams increased by 1.32 to 2.22 times compared to the control, clearly demonstrating the efficacy of fiber reinforcement in improving structural performance. Specifically, the control beam served as the baseline for comparison, and the incorporation of PVA fibers in the PVCC mixtures significantly elevated the stiffness values. However, it was observed that PVCC mixtures with higher fiber content experienced slight reductions in stiffness compared to the peak enhancement, yet they still maintained significantly elevated stiffness levels relative to the control beam. This behavior indicates that while there may be an optimal range for fiber content to maximize stiffness, even higher contents do not negate the benefits entirely. This analysis is crucial for structural integrity assessments, as it underscores the effectiveness of PVA fiber in enhancing beam stiffness, thereby contributing to the overall robustness and durability of reinforced concrete structures. These findings highlight the potential for incorporating PVA fibers in concrete to improve the structural performance of beams, making them more resilient and reliable in various construction applications.

Energy Absorption and Energy Index

The energy absorption capacity of reinforced concrete beams was assessed by integrating the load-deflection curve, a critical parameter for evaluating structural safety under seismic conditions. The results, as reported by Mohanraj et al. (2023), demonstrated varying energy absorption capacities among the control and PVCC layered beams. The energy absorption values were graphically represented in Figure 7, illustrating the comparative performance.

Additions of 0.4% and 0.8% PVA fiber increased the energy absorption capacity by 1.04 to 1.20 times compared to the control beam. Notably, the PVCC layered beam with 1.2% PVA fiber (BP3) exhibited the highest energy absorption, surpassing the control beam by 1.49 times. This indicates that BP3 has a superior capacity for energy dissipation, which is crucial during seismic events. However, further increases in fiber content in BP4 (1.6% PVA fiber) and BP5 (2% PVA fiber) led to decreased energy absorption compared to BP3, although still higher than the control beam. This trend highlights that while the inclusion of PVA fibers generally enhances energy absorption, there is an optimal fiber content – specifically, 1.2% in this case – that maximizes performance. Liu et al. (2024) findings underscore the importance of optimizing fiber content to achieve the best balance between material enhancement and practical application, thereby ensuring improved energy dissipation and structural resilience during seismic activity.

The energy index of the specimens reflects the ratio of energy absorbed until the ultimate load to that absorbed until the first crack, serving as a key indicator of the material's performance under stress. The control beam (B0) exhibited an energy index of 3.66, setting the baseline for comparison. The incorporation of 0.4% and 0.8% PVA fiber in the PVCC layered beams increased the energy index by 1.01 to 1.38 times compared to the control beam. This demonstrates the positive impact of PVA fiber addition on the energy absorption efficiency of the beams. Notably, the PVCC layered beam with 1.2% PVA fiber (BP3) demonstrated a significantly higher energy index, 1.53 times that of the control beam (B0). This indicates that BP3 has an optimal combination of fiber content, enhancing its ability to absorb energy effectively before reaching the ultimate load. Although the beams with higher PVA fiber content, BP4 (1.6% PVA fiber) and BP5 (2% PVA fiber), exhibited slight decreases in energy index compared to BP3, their indices were still 1.23 and 1.02 times higher than B0, respectively. These results highlight BP3's superior performance in terms of energy absorption and dissipation, showcasing the importance of optimizing fiber content for maximum structural benefits. The findings suggest that while increasing PVA fiber

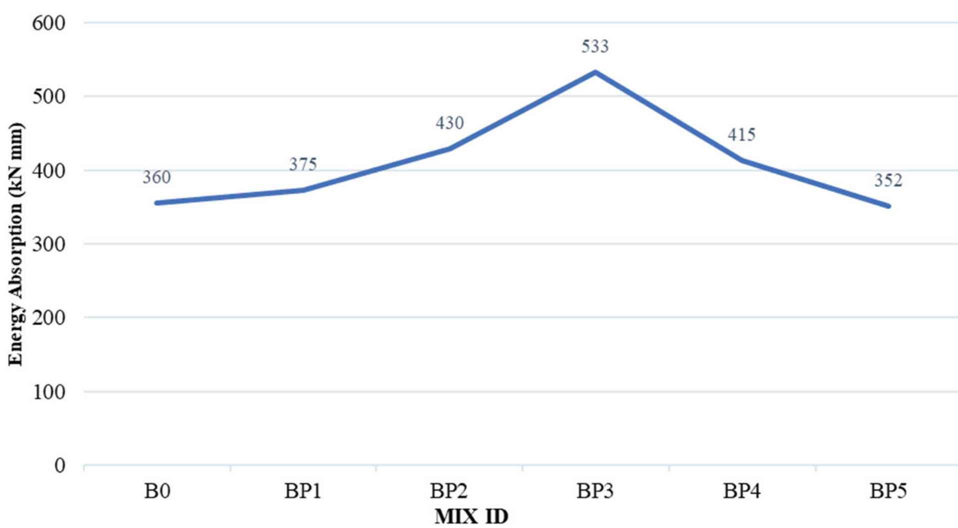

Figure 7. Energy absorption of control and PVCC layered beams.

content generally enhances energy absorption, there is an optimal fiber percentage—1.2% in this study – that provides the best balance, leading to improved performance in energy dissipation and overall structural resilience.

Conclusion

(1) The investigation identified distinct thresholds in the first crack load of PVCC-layered reinforced concrete beams containing coal ash (BP1 to BP5) as compared to the control specimen (B0). The control specimen exhibited an initial fracture initiation load of 80kN, however subsequent specimens had different crack initiation values based on the amount of PVA fiber utilized. Notably, specimens with higher PVA fiber content exhibited earlier fracture initiation, demonstrating the importance of fiber dosage in the structural behavior of PVCC-layered concrete beams. The insertion of PVA fibers to PVCC multilayer beams resulted in significant improvements in ultimate load-carrying capability. Specimens with higher fiber content had larger ultimate loads than the control specimen, with an ideal dosage of 1.2% PVA fiber discovered. However, excessive fiber content led to slight decreases in ultimate load, emphasizing the importance of dosage optimization for maximizing load-bearing capacity.

(2) PVCC-layered reinforced concrete beams outperformed control specimens in terms of load-deflection behavior. Specimen BP3 demonstrated improved load-bearing capacity and deflection resistance due to appropriate fiber content. Multiple crack propagations were detected without beam splitting, demonstrating the structural stability of PVCC-layered beams under stress circumstances. Ductility assessments revealed significant improvements with PVA fiber reinforcement in PVCC layered beams. Specimens incorporating higher fiber content exhibited enhanced ductility compared to the control, particularly with 1.2% PVA fiber dosage. However, excessive fiber content led to diminishing returns, indicating an optimal dosage range for maximizing ductility while maintaining structural integrity.

(3) Evaluation of stiffness demonstrated notable enhancements with PVA fiber addition in PVCC layered beams. The stiffness increased substantially compared to the control, showcasing the efficacy of fiber reinforcement in improving beam rigidity and structural integrity. Despite slight reductions with higher fiber content, stiffness remained significantly elevated, highlighting the overall effectiveness of PVA fiber in enhancing structural performance. Assessment of energy absorption capacity indicated varying performance among control and PVCC layered beams. Specimens incorporating PVA fiber exhibited increased energy absorption compared to the control, with optimal performance observed at 1.2% PVA fiber dosage. However, excessive fiber content led to diminishing energy absorption, emphasizing the importance of dosage optimization for maximizing structural resilience.

(4) The energy index analysis provided insights into the efficiency of energy dissipation in PVCC layered beams. Specimens featuring higher PVA fiber content demonstrated superior energy indices compared to the control, particularly at 1.2% PVA fiber dosage. Although excessive fiber content led to slight decreases in energy indices, specimens exhibited improved energy dissipation compared to the control, highlighting the overall effectiveness of PVA fiber reinforcement in enhancing structural performance.

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References

Ahmed, S., and H. Mihashi. 2011. “Strain Hardening Behavior of Lightweight Hybrid Polyvinyl Alcohol (PVA) Fiber Reinforced Cement Composites.” *Materials and Structures* 44 (6): 1179–1191. https://doi.org/10.1617/s11527-010-9691-8.

Aljarrah, M. T., and N. R. Abdelal. 2019. “Improvement of the Mode I Interlaminar Fracture Toughness of Carbon Fiber Composite Reinforced with Electrospun Nylon Nanofiber.” *Composites Part B Engineering* 165:379–385. https://doi.org/10.1016/j.compositesb.2019.01.065.

Amusan, G. M. 2024. “Structural Strength Characteristics of Coal Ash Blended Cement Concrete Exposed to Coastal Environment.” *Cankaya University Journal of Science and Engineering* 21 (1): 33–41.

Ankur, N., and N. Singh. 2024b. “Strength Characterization and Sustainability Assessment of Coal Bottom Ash Concrete.” *Environmental Science and Pollution Research*: 1–38. https://doi.org/10.1007/s11356-024-33303-z.

Cai, J., J. Jiang, X. Gao, and M. Ding. 2022. “Improving the Mechanical Properties of Fly Ash-Based Geopolymer Composites with PVA Fiber and Powder.” *Materials* 15 (7): 2363. https://doi.org/10.3390/ma15072363.

Che, J., Z. Guo, Q. Li, and H. Liu. 2022. “Mechanical Properties of Desert-Sand-Based Steel-PVA Hybrid Fiber Reinforced Engineered Cementitious Composites (H-DSECC).” *KSCE Journal of Civil Engineering* 26 (12): 5160–5172. https://doi.org/10.1007/s12205-022-1746-1.

Domke, P. V., S. D. Deshmukh, S. D. Kene, and R. Deotale. 2011. “Study of Various Characteristic of Concrete with Rice Husk Ash as a Partial Replacement of Cement with Natural Fibers (Coir).” *International Journal of Engineering Research and Applications (IJERA)* 1 (3): 554–562.

Ghosal, M. 2023. “Development of Coal Ash for Structural Applications.” In Singh, S. B., Gopalarathnam, M., R. Kodur, V. K., and Matsagar, V. A. (Eds.), *Fiber reinforced polymeric materials and sustainable structures* (pp. 289–296). Singapore: Springer Nature Singapore.

Golewski, G. L. 2023. “The Effect of the Addition of Coal Fly Ash (CFA) on the Control of Water Movement within the Structure of the Concrete.” *Materials* 16 (15): 5218. https://doi.org/10.3390/ma16155218.

Gupta, P. K., and V. K. Verma. 2016. “Study of Concrete-Filled Unplasticized Poly-Vinyl Chloride Tubes in Marine Environment.” *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment* 230 (2): 229–240. https://doi.org/10.1177/1475090214560448.

Haincová, E., and P. Hájková. 2020. “Effect of Boric Acid Content in Aluminosilicate Matrix on Mechanical Properties of Carbon Prepreg Composites.” *Materials* 13 (23): 5409. https://doi.org/10.3390/ma13235409.

Ibrahim, A. A., H. Najla’a, M. H. Jaber, R. F. Hassan, H. H. Hussein, and N. H. Al-Salim. 2022. “Experimental Investigation of Flexural and Shear Behaviors of Reinforced Concrete Beam Containing Fine Plastic Waste Aggregates.” *Structures* 43:834–846. https://doi.org/10.1016/j.istruc.2022.07.019.

Karbhari, V. M., D. Wang, and Y. Gao. 2001. "Processing and Performance of Bridge Deck Subcomponents Using Two Schemes of Resin Infusion." *Composite Structures* 51 (3): 257–271. https://doi.org/10.1016/S0263-8223(00)00136-7.

Kendall, A., G. A. Keoleian& Michael D Lepech, and M. D. Lepech. 2008. "Materials Design for Sustainability Through Life Cycle Modeling of Engineered Cementitious Composites." *Materials and Structures* 41 (6): 1117–1131. https://doi.org/10.1617/s11527-007-9310-5.

Khan, M. K. I., Y. X. Zhang, and C. K. Lee. 2021. "Mechanical Properties of High-Strength Steel–Polyvinyl Alcohol Hybrid Fibre Engineered Cementitious Composites." *Journal of Structural Integrity & Maintenance* 6 (1): 47–57. https://doi.org/10.1080/24705314.2020.1823558.

Kim, J. E., J. Seo, K. H. Yang, and H. K. Kim. 2023. "Cost and CO2 Emission of Concrete Incorporating Pretreated Coal Bottom Ash as Fine Aggregate: A Case Study." *Construction and Building Materials* 408:133706. https://doi.org/10.1016/j.conbuildmat.2023.133706.

Kumar, A. P., D. Maneiah, and L. P. Sankar. 2021. "Improving the Energy-Absorbing Properties of Hybrid Aluminum-Composite Tubes Using Nanofillers for Crashworthiness Applications." *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 235 (8): 1443–1454. https://doi.org/10.1177/0954406220942267.

Kumar, S., T. Mukhopadhyay, S. A. Waseem, B. Singh, and M. A. Iqbal. 2016. "Effect of Platen Restraint on Stress–Strain Behavior of Concrete Under Uniaxial Compression: A Comparative Study." *Strength of Materials* 48 (4): 592–602. https://doi.org/10.1007/s11223-016-9802-z.

Lee, D., S. C. Lee, and S. W. Yoo. 2023. "Bond Behavior of Steel Rebar Embedded in Cementitious Composites Containing Polyvinyl Alcohol (PVA) Fibers and Carbon Nanotubes (CNTs)." *Polymers* 15 (4): 884. https://doi.org/10.3390/polym15040884.

Lepech, M. D., and V. C. Li. 2009. "Application of ECC for Bridge Deck Link Slabs." *Materials and Structures* 42 (9): 1185–1195. https://doi.org/10.1617/s11527-009-9544-5.

Liu, K., G. Lin, Y. Chen, and H. Li. 2024. "Study on Cyclic Mechanical Behavior and Damage Constitutive of PVA Fiber Recycled Aggregate Concrete." *Iranian Journal of Science & Technology, Transactions of Civil Engineering* 1–18. https://doi.org/10.1007/s40996-024-01385-x.

Loganathan, P., R. Mohanraj, S. Senthilkumar, and K. Yuvaraj. 2022. "Mechanical Performance of etc RC Beam with U-Framed AFRP Laminates Under a Static Load Condition." *Revista de la Construcción: Journal of Construction* 21 (3): 678–691. https://doi.org/10.7764/RDLC.21.3.678.

Mamadaliyev, X. E., and F. X. Fazilov. 2024. "Prospects for the Use of Coal Ash in the Construction Industry." *International Journal of Scientific Trends* 3 (2): 45–48.

Meena, A., N. Singh, and S. P. Singh. 2024. "Shear Strength and Microstructural Investigation on High-Volume Fly Ash Self-Compacting Concrete Containing Recycled Concrete Aggregates and Coal Bottom Ash." *Materiales de Construcción* 74 (353): e333–e333. https://doi.org/10.3989/mc.2024.354623.

Meng, D., T. Huang, Y. X. Zhang, and C. K. Lee. 2017. "Mechanical Behaviour of a Polyvinyl Alcohol Fibre Reinforced Engineered Cementitious Composite (PVA-ECC) Using Local Ingredients." *Construction and Building Materials* 141:259–270. https://doi.org/10.1016/j.conbuildmat.2017.02.158.

Mohanraj, R., S. Senthilkumar, P. Goel, and R. Bharti. 2023. "A State-Of-The-Art Review of Euphorbia Tortilis Cactus as a Bio-Additive for Sustainable Construction Materials." *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2023.03.762.

Mohanraj, R., S. Senthilkumar, and P. Padmapoorani. 2022. "Mechanical Properties of RC Beams with AFRP Sheets Under a Sustained Load." *Materials and Technology* 56 (4): 365–372. https://doi.org/10.17222/mit.2022.481.

Mohanraj, R., and K. Vidhya. 2024. "Evaluation of Compressive Strength of Euphorbia Tortilis Cactus Infused M25 Concrete by Using ABAQUS Under Static Load." *Materials Letters* 356:135600. https://doi.org/10.1016/j.matlet.2023.135600.

Mpalaskas, A. C., D. G. Aggelis, and T. E. Matikas. 2021. "Monitoring the Fracture Behavior of Epoxy Resin Repaired Fiber Reinforced Concrete Specimens by Acoustic Emission." In *Sensors and smart structures technologies for civil, mechanical, and aerospace systems 2021*, 461–474. Vol. 11591. SPIE. March. https://doi.org/10.1117/12.2584603.

Muhammed, A., P. Thangaraju, and S. Shanmugamoorthy. 2023. "Assessment on Durability of Lightweight Concrete Using Alkali Modified Fly Ash Based Atrificial Coarse Aggregate

(FACA)." *International Journal of Coal Preparation & Utilization* 43 (11): 1829–1847. https://doi.org/10.1080/19392699.2022.2139248.

Nanjappan, S. A., S. Manogaran, B. J. Alphonse, H. Balasubramanian, and N. A. Razack. 2024. "Experimental and Statistical Study of Flexural Strength in Concrete Using Novel Kaolinite Coal." In E3S Web of Conferences, 02046. Tamilnadu, India: EDP Sciences. https://doi.org/10.1051/e3sconf/202449102044.

Naoum, M. C., N. A. Papadopoulos, M. E. Voutetaki, and C. E. Chalioris. 2023. "Structural Health Monitoring of Fiber-Reinforced Concrete Prisms with Polyolefin Macro-Fibers Using a Piezoelectric Materials Network Under Various Load-Induced Stress." *Buildings* 13 (10): 2465. https://doi.org/10.3390/buildings13102465.

Padmapoorani, P., S. Senthilkumar, and R. Mohanraj. 2023. "Machine Learning Techniques for Structural Health Monitoring of Concrete Structures: A Systematic Review." *Iranian Journal of Science & Technology, Transactions of Civil Engineering* 47 (4): 1919–1931. https://doi.org/10.1007/s40996-023-01054-5.

Pan, Z., C. Wu, J. Liu, W. Wang, and J. Liu. 2015. "Study on Mechanical Properties of Cost-Effective Polyvinyl Alcohol Engineered Cementitious Composites (PVA-ECC)." *Construction and Building Materials* 78:397–404. https://doi.org/10.1016/j.conbuildmat.2014.12.071.

Parghi, A., and M. S. Alam. 2018. "A Review on the Application of Sprayed-FRP Composites for Strengthening of Concrete and Masonry Structures in the Construction Sector." *Composite Structures* 187:518–534. https://doi.org/10.1016/j.compstruct.2017.11.085.

Pattusamy, L., M. Rajendran, S. Senthilkumar, and R. Krishnasamy. 2023. "Confinement Effectiveness of 2900psi Concrete Using the Extract of Euphorbia Tortilis Cactus as a Natural Additive." *Matéria (Rio de Janeiro)* 28 (1). https://doi.org/10.1590/1517-7076-RMAT-2022-0233.

Praveen Kumar, A. 2019. "Experimental Analysis on the Axial Crushing and Energy Absorption Characteristics of Novel Hybrid Aluminium/composite-Capped Cylindrical Tubular Structures." *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 233 (11): 2234–2252. https://doi.org/10.1177/1464420719843157.

Raj, B. S., and M. K. Rao. 2023. "Flexural Performance of Sustainable Fly Ash Based Concrete Beams." *IOP Conference Series: Earth and Environmental Science* 1130 (1): 012021. https://doi.org/10.1088/1755-1315/1130/1/012021.

Raju, S., and B. Dharmar. 2016. "Mechanical Properties of Concrete with Copper Slag and Fly Ash by DT and NDT." *Periodica Polytechnica Civil Engineering* 60 (3): 313–322. https://doi.org/10.3311/PPci.7904.

Sadrmomtazi, A., M. Khabaznia, and B. Tahmouresi. 2016. "Effect of Organic and Inorganic Matrix on the Behavior of FRP-Wrapped Concrete Cylinders." *Journal of Rehabilitation in Civil Engineering* 4 (2): 52–66.

Saleh, H. M., I. I. Bondouk, E. Salama, H. H. Mahmoud, K. Omar, and H. A. Esawii. 2022. "Asphaltene or Polyvinylchloride Waste Blended with Cement to Produce a Sustainable Material Used in Nuclear Safety." *Sustainability* 14 (6): 3525. https://doi.org/10.3390/su14063525.

Saravanakumar, R., K. S. Elango, V. Revathi, and D. Balaji. 2024. "Influence of Aggressive Environment in Macro and Microstructural Properties of Bottom Ash Geopolymer Concrete." *Sustainability* 16 (5): 1732. https://doi.org/10.3390/su16051732.

Sen, T., and J. Reddy. 2011. "Hn 'Finite Element Simulation of Retrofitting of RCC Beam Using Coir Fiber Composite (Natural Fiber)." *International Journal of Innovation, Management and Technology* 2 (2): 175–179.

Shanmugasundaram, S., R. Mohanraj, S. A. P. Senthilkumar, and P. Padmapoorani. 2022. "Torsional Performance of Reinforced Concrete Beam with Carbon Fiber and Aramid Fiber Laminates." *Revista de la Construcción: Journal of Construction* 21 (2): 329–337. https://doi.org/10.7764/RDLC.21.2.329.

Sun, M., Y. Chen, J. Zhu, T. Sun, Z. Shui, G. Ling, and Y. Zheng. 2018. "Effect of Modified Polyvinyl Alcohol Fibers on the Mechanical Behavior of Engineered Cementitious Composites." *Materials* 12 (1): 37. https://doi.org/10.3390/ma12010037.

Thomoglou, A. K., M. G. Falara, F. I. Gkountakou, A. Elenas, and C. E. Chalioris. 2022. “Influence of Different Surfactants on Carbon Fiber Dispersion and the Mechanical Performance of Smart Piezoresistive Cementitious Composites.” *Fibers* 10 (6): 49. https://doi.org/10.3390/fib10060049.

Thomoglou, A. K., M. G. Falara, M. E. Voutetaki, J. G. Fantidis, B. A. Tayeh, and C. E. Chalioris. 2023. “Electromechanical Properties of Multi-Reinforced Self-Sensing Cement-Based Mortar with MWCNTs, CFs, and PPs.” *Construction and Building Materials* 400:132566. https://doi.org/10.1016/j.conbuildmat.2023.132566.

Velumani, M., R. Mohanraj, R. Krishnasamy, and K. Yuvaraj. 2023. “Durability Evaluation of Cactus-Infused M25 Grade Concrete as a Bio-Admixture.” *Periodica Polytechnica Civil Engineering* 67 (4): 1066–1079. https://doi.org/10.3311/PPci.22050.

Wang, Z. B., S. Han, P. Sun, W. K. Liu, and Q. Wang. 2021. “Mechanical Properties of Polyvinyl Alcohol-Basalt Hybrid Fiber Engineered Cementitious Composites with Impact of Elevated Temperatures.” *Journal of Central South University* 28 (5): 1459–1475.

Wang, Z., P. Wang, and F. Zhu. 2022. “Synergy Effect of Hybrid Steel-Polyvinyl Alcohol Fibers in Engineered Cementitious Composites: Fiber Distribution and Mechanical Performance.” *Journal of Building Engineering* 62:105348. https://doi.org/10.1016/j.jobe.2022.105348.

Yong Kim, Y., H.-J. Kong, and V. C. Li. 2003. “Design of Engineered Cementitious Composite Suitable for Wet-Mixture Shotcreting.” *ACI Materials Journal* 100 (6): 511–518.

Zhang, D., T. Zhu, Q. Ai, M. Mao, J. Li, and Q. Yang. 2024. “Performance of Coal Gangue Concrete with Fly Ash and Ground-Granulated Blast Slag: Rheology, Mechanical Properties and Microstructure.” *Construction and Building Materials* 427:136250. https://doi.org/10.1016/j.conbuildmat.2024.136250.

Zong, G., X. Hao, J. Hao, W. Tang, Y. Fang, R. Ou, and Q. Wang. 2020. “High-Strength, Lightweight, Co-Extruded Wood Flour-Polyvinyl Chloride/Lumber Composites: Effects of Wood Content in Shell Layer on Mechanical Properties, Creep Resistance, and Dimensional Stability.” *Journal of Cleaner Production* 244:118860. https://doi.org/10.1016/j.jclepro.2019.118860.