



Mechanical Performance of Basalt Fibre-Reinforced Geopolymer Matrix Synthesized from Agro-Waste Ashes

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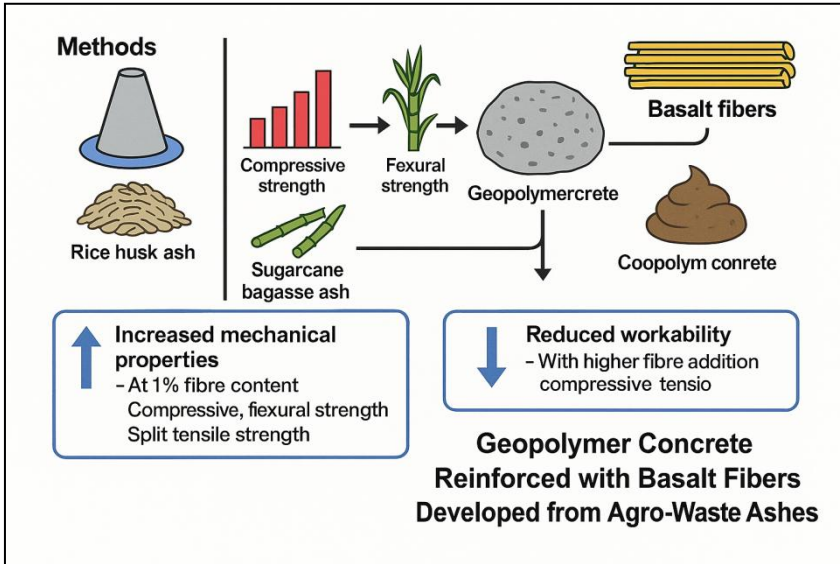
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Abstract. This study explores the influence of basalt fibres incorporation on the fresh and hardened properties of geopolymer concrete developed from agro-waste ashes—namely rice husk ash, sugarcane bagasse ash, and cow dung ash. Seven distinct mixes were prepared with varying basalt fibre contents ranging from 0% to 2.5% by weight. The performance of each mix was assessed through workability (slump), compressive strength, flexural strength, and split tensile strength at 7, 28, and 90 days of curing. Results revealed that the inclusion of basalt fibres significantly improved the tensile and flexural response of the geopolymer matrix up to an optimum fibre content of 1%. Beyond this threshold, mechanical strength declined. The reference mix without fibres exhibited the highest slump retention, while higher fibre additions reduced flowability considerably. Among all combinations, the RSCB-1 mix demonstrated the most favorable balance between mechanical enhancement and workable consistency. The findings underscore the potential of combining agricultural waste ashes with optimally dosed basalt fibres to develop sustainable, high-performance geopolymer concrete suitable for structural applications.

Keywords: Geopolymer Concrete, Basalt Fibres, Agro-Waste Ashes, Mechanical Properties, Workability, Sustainable Construction.

Graphical Abstract



1. Introduction

The growing concern over environmental degradation and the rapid depletion of natural resources has led to an urgent need for sustainable alternatives in the construction sector. Traditional Portland cement production is associated with high energy consumption and considerable carbon dioxide emissions, prompting researchers and engineers to seek eco-friendly binders[1]. Geopolymers have emerged as a promising class of alternative materials due to their low carbon footprint, excellent durability, and the ability to incorporate industrial or agricultural waste [2].

Among the various waste-derived materials, rice husk ash, sugarcane bagasse ash, and cow dung ash have gained attention for their pozzolanic properties and abundance, particularly in regions with large agricultural economies[3-5]. These ashes are rich in silica and other mineral constituents, which play a crucial role in the geopolymerization process, forming strong aluminosilicate networks. Their effective utilization not only reduces the load on landfills but also adds value to materials that are otherwise considered waste [6-8].

In parallel, the addition of fibres to concrete and geopolymer systems has been known to enhance mechanical properties, particularly tensile and flexural strength. Basalt fibres, produced from naturally occurring volcanic rock, offer high tensile strength, thermal stability, and chemical resistance, making them suitable for reinforcing cement-free binders. When properly dispersed, these fibres bridge microcracks and delay crack propagation, thereby improving the toughness and ductility of the composite[9-13].

This study investigates the combined use of agricultural ashes and basalt fibres in developing a geopolymer concrete system that is both structurally sound and environmentally responsible. By varying the fibre content, the research aims to understand the effect of fibre dosage on workability, compressive strength, flexural strength, and split tensile strength over multiple curing periods. The outcomes are expected to guide the formulation of optimized geopolymer mixes for practical and sustainable construction applications.

2. Materials used

The primary constituents employed in the development of the geopolymer concrete mixes were selected based on their availability, chemical suitability, and environmental sustainability. A careful combination of industrial by-products and natural reinforcements was adopted to meet both performance and ecological objectives. RHA, obtained from controlled combustion of rice husks, served as a key source of reactive silica. The ash was finely sieved and used in dry form. Its high amorphous silica content made it an effective component for the geopolymer binder, contributing to long-term strength and chemical stability. SBA was collected from sugar manufacturing units where sugarcane residue is used as a fuel source. Prior to use, it was dried, ground, and passed through standard sieves to ensure particle size consistency. Rich in silica and alumina, SBA plays a vital role in the geopolymerization process by enhancing the binder matrix. Cow dung ash (CDA) was derived from the open-air burning of sun-dried cow dung cakes. The ash was processed to remove unburnt organic matter and then sieved for uniformity. Known for its unique blend of minerals, CDA complements the reactivity of RHA and SCBA and improves the sustainability quotient of the binder system. A blend of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions was used to initiate the geopolymer reaction. The sodium hydroxide solution was prepared at a specified molarity using laboratory-grade pellets dissolved in distilled water, while the sodium silicate solution was commercially sourced with predefined composition. The ratio of the two components was adjusted based on prior optimization trials to balance workability and strength development. Natural river sand conforming to standard grading requirements was used as the fine aggregate. It was clean, free from organic impurities, and ensured adequate flow and cohesion in the fresh mix. Chopped basalt fibres, cut to a consistent length, were introduced to improve tensile and flexural characteristics. The fibres were dosed by weight percentage of the binder and mixed gradually to ensure even distribution. Basalt fibres were selected for their natural origin, high tensile strength, and resistance to chemical and thermal degradation. Table 1 shows the physical and chemical properties of precursor materials and fibres used.

Table 1: Physical and chemical properties of materials used.

Physical and chemical properties	RHA	SBA	CDA	Basalt Fibres
Size (mm)	--	--	--	12 mm
Fineness (Passing 45 μm)	3	3.1	3.4	--
Specific gravity (kg/cm^3)	2.12	2.3	2.1	2.6
Al_2O_3 (%)	0.19	9	17	18

SiO ₂ (%)	90.3	64	61	53
CaO (%)	0.71	11	9.5	4.8
Fe ₂ O ₃ (%)	0.1	0.6	3.5	9
MgO (%)	--	4.5	--	5
Na ₂ O (%)	--	1.7	--	6.2
TiO ₂ (%)	--	0.1	--	2
FeO (%)	--	--	--	--
SO ₃ (%)	1.8	--	--	--
K ₂ O (%)	--	4	--	--
P ₂ O ₅ (%)	--	1.1	--	--
LOI (%)	3.12	2	--	--
Others (%)	3.78	2	9	2.27

3. Methodology

This experimental program was structured to examine the effects of basalt fibre incorporation on the mechanical and fresh properties of geopolymer concrete synthesized from agro-waste-based binders. The methodology was executed in a series of controlled steps to ensure consistency and reproducibility across all mix variations. The ashes—rice husk ash, sugarcane bagasse ash, and cow dung ash—were collected from local sources. These were subjected to drying, grinding, and sieving through a 75-micron mesh to achieve a uniform fine texture suitable for geopolymer binder formulation. All materials were stored in airtight containers to avoid moisture absorption prior to use. The alkaline activator solution was formulated by mixing sodium hydroxide and sodium silicate in a pre-determined ratio. Sodium hydroxide pellets were dissolved in distilled water to obtain the required molarity. This solution was allowed to cool to ambient temperature before blending with the sodium silicate solution. The prepared activator was stored in sealed containers for at least 24 hours before usage to stabilize the chemical reaction potential. A base mix was designed with a fixed ratio of binder to sand and a constant activator-to-binder ratio. Seven different batches were prepared, each with varying basalt fibre content: 0%, 0.1%, 0.5%, 1%, 1.5%, 2%, and 2.5% by weight of binder. The control mix (RSCB0) had no fibres, serving as a benchmark for comparison. Fibres were weighed precisely and manually distributed into the dry mix to avoid clumping. Dry materials—ashes and fine aggregate—were thoroughly mixed to ensure uniformity. The basalt fibres were added gradually during this dry mixing phase. After homogeneous distribution was achieved, the alkaline solution was slowly added while continuously mixing until a cohesive paste formed. Care was taken to ensure uniform wetting and fibre dispersion. Mix design procedure of Mahapara and Gyanendra [14] was followed here in this study. The fresh geopolymer mix was poured into standard moulds for testing: cubes (150 mm) for compressive strength, beams (100 mm × 100 mm × 500 mm) for flexural strength, and cylinders (100 mm diameter × 200 mm height) for split tensile strength. Each mould was filled in layers and compacted manually and through table vibration to eliminate entrapped air. Immediately after casting, all specimens were left undisturbed at room temperature for 24 hours. After demoulding, they were stored under ambient conditions without heat treatment, to simulate practical on-site curing. Tests were conducted at 7, 28, and 90 days to assess performance over time.

4. Results and Discussion

4.1. Workability

The Figure 1 presents the variation in slump over time for several geopolymers concrete compositions formulated with a combination of **Rice Husk Ash (R)**, **Sugarcane Bagasse Ash (S)**, **Cow Dung Ash (C)**, and varying proportions of **Basalt Fibres (B)**. These mixes, coded from RSCB0 to RSCB2.5, were evaluated at different time intervals—0, 20, 40, 60, and 80 minutes—to assess their workability retention characteristics. At the initial time mark (0 minutes), the reference mix **RSCB0** (without basalt fibres) exhibited the highest slump value, indicating superior initial flowability. As basalt fibres were introduced incrementally from 0.1% up to 2.5% by weight of binder, a progressive decline in slump was observed across all time intervals. This reduction in slump can be attributed to the inherent **absorptive capacity and surface area** of basalt fibres, which tend to restrict the free movement of particles in the fresh mix and draw in a portion of the mix water or alkaline solution [3], [4], [15].

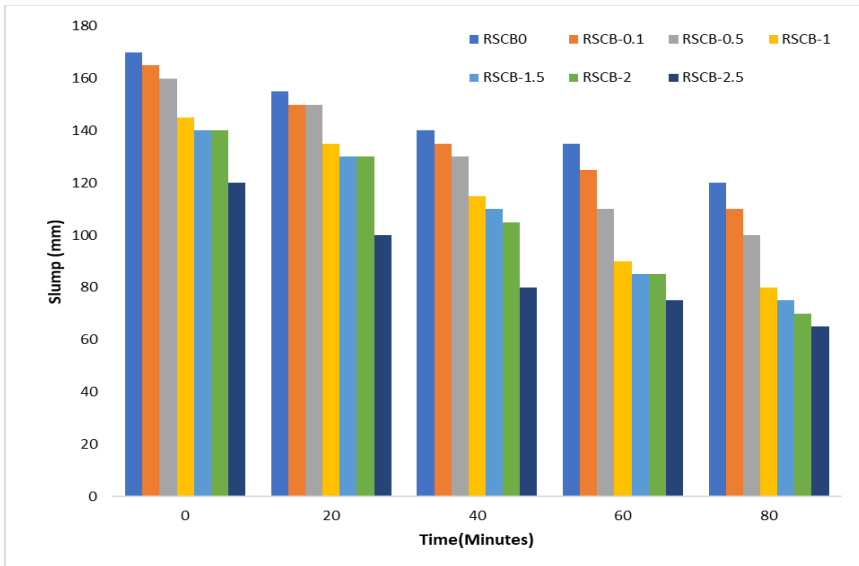


Figure 1: Workability of the mixes.

The most prominent drop in workability was seen in the **RSCB2.5** mix, especially evident by the 80-minute mark, where the slump dropped significantly below that of all other mixes. This trend indicates that at higher fibre dosages, the mixture becomes increasingly stiff over time, thereby reducing its usability period and requiring either additional mixing energy or workability-enhancing admixtures for practical applications[16-17]. It is also evident that the rate of slump loss over time is steeper as the fibre content increases. For instance, between 0 and 80 minutes, the slump reduction in RSCB0 is modest, maintaining a relatively workable consistency, whereas in RSCB2.5, the loss is drastic, suggesting that higher fibre content accelerates the stiffening process of the mix[18-21].

4.2. Compressive strength

From Figure 2 the compressive strength data across 7, 28, and 90 days reveal an insightful trend concerning the influence of basalt fibre dosage in geopolymer composites made with rice husk ash (R), sugarcane bagasse ash (S), and cow dung ash (C). The reference mix RSCB0, without any fibres, sets the baseline, showing moderate strength gain over time. However, the addition of basalt fibres, even in small amounts, alters the performance significantly. As the basalt fibre content increases up to 1% by weight (RSCB-1), a clear improvement in strength is observed at all curing ages. This enhancement is most notable at 90 days, where the mix peaks in performance, indicating that 1% fibre content provides optimal crack-bridging, matrix integrity, and internal load distribution. This synergistic interaction likely enhances the interfacial bond between the binder matrix and fibres, leading to more effective stress transfer [22-25]. Beyond this optimum (i.e., mixes RSCB-1.5, RSCB-2, and RSCB-2.5), the strength begins to decline.

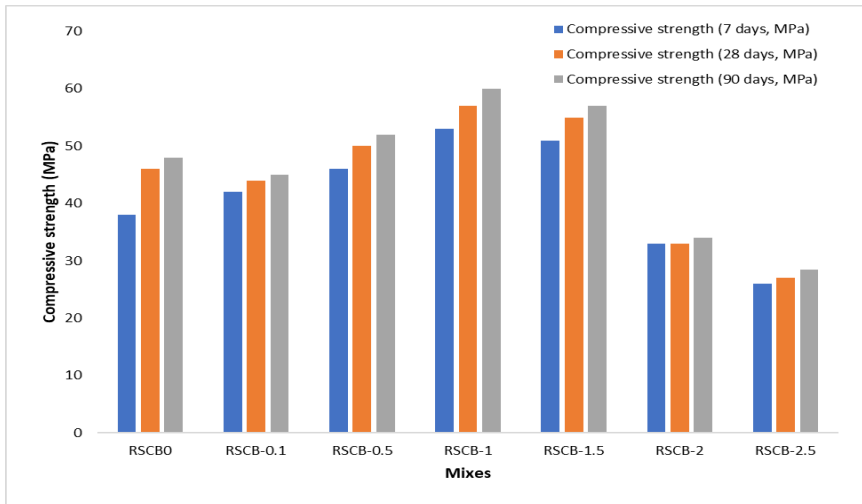


Figure 2: Compressive strength of the mixes

The excessive fibre dosage possibly leads to fibre clustering, poor dispersion, and increased internal voids, all of which compromise the integrity of the hardened matrix. These defects likely interrupt the continuity of the geopolymer gel network, thereby hindering its strength-gaining potential. Notably, RSCB-2.5 records the lowest compressive strength across all test durations, showing that excessive fibre incorporation adversely affects both early-age and long-term performance [26-28]. Interestingly, while all mixes continue to gain strength from 7 to 90 days, the rate of strength development is more pronounced in fibre-containing mixes up to 1%, after which the gains taper off or stagnate. This observation implies that controlled fibre inclusion enhances not just the peak strength but also the curing kinetics, particularly the development of the aluminosilicate network that characterizes geopolymer concretes [29-31].

4.3. Flexural strength

The variation in flexural strength across the RSCB series, measured at 7, 28, and 90 days, in Figure 3 provides a clear picture of how fibre content influences the bending performance of geopolymer composites composed of rice husk ash, sugarcane bagasse ash, and cow dung ash, along with different proportions of basalt fibres. Initially, the reference mix RSCB0, which contains no fibres, displays modest flexural strength that increases with curing age. However, the incorporation of fibres brings about a significant enhancement, particularly up to 1% fibre content (RSCB-1). This mix stands out with the highest flexural strength at all curing ages, reaching a peak of over 5 MPa at 90 days.

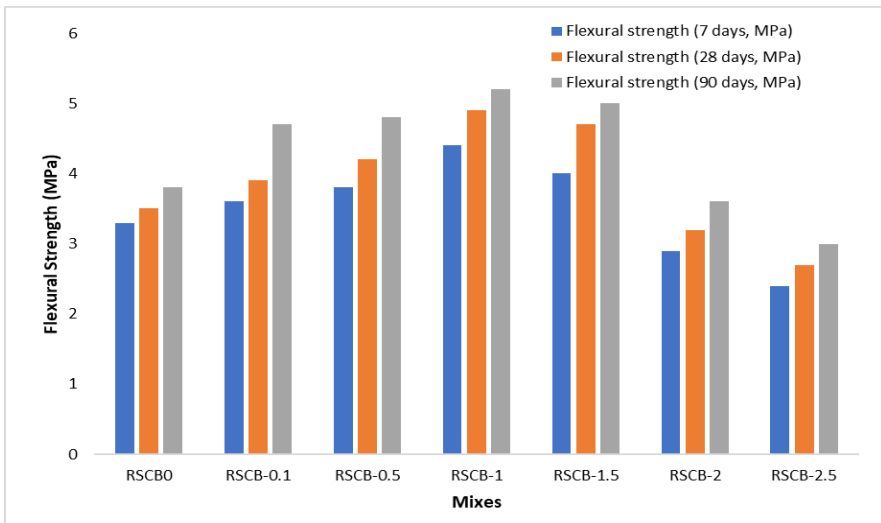


Figure 3: Flexural strength of the mixes

This suggests that 1% basalt fibre strikes an effective balance, offering enough reinforcement to bridge microcracks and resist tensile forces while still allowing good fibre dispersion and matrix bonding[20], [32-35]. Beyond the 1% level, the performance begins to taper. In RSCB-1.5, the strength remains high but slightly lower than RSCB-1. This minor dip hints at the onset of fibre saturation, where too many fibres may start to hinder optimal matrix flow and packing. In mixes with 2% and 2.5% fibre content, the flexural strength drops more noticeably. The reduction can be attributed to fibre clumping, poor orientation, and increased void content, all of which undermine the tensile stress distribution capabilities of the composite[3], [4], [23], [33].

4.4. Split tensile strength

The graphical data presented in Figure 4 illustrates how the inclusion of basalt fibres influences the split tensile strength of geopolymer mixes derived from rice husk ash, sugarcane bagasse ash, and cow dung ash. The results are presented across three curing durations: 7, 28, and 90 days. The general pattern shows that moderate inclu-

sion of fibres enhances tensile resistance, but excessive quantities may have adverse effects. Starting with the control mix RSCB0, the values show a steady increase from early to late age, indicating that the geopolymerization process continues to contribute positively to strength development[25, 36-37]. Upon adding fibres at a 0.1% dosage (RSCB-0.1), there is a visible improvement in all curing stages. This increase suggests that even a minimal amount of fibres begins to impact the material's ability to resist tensile forces by forming micro-reinforcement bridges within the matrix. As fibre content increases to 0.5% and then 1%, the tensile performance improves further, reaching its maximum at RSCB-1, which exhibits the highest split tensile strength values across all time points.

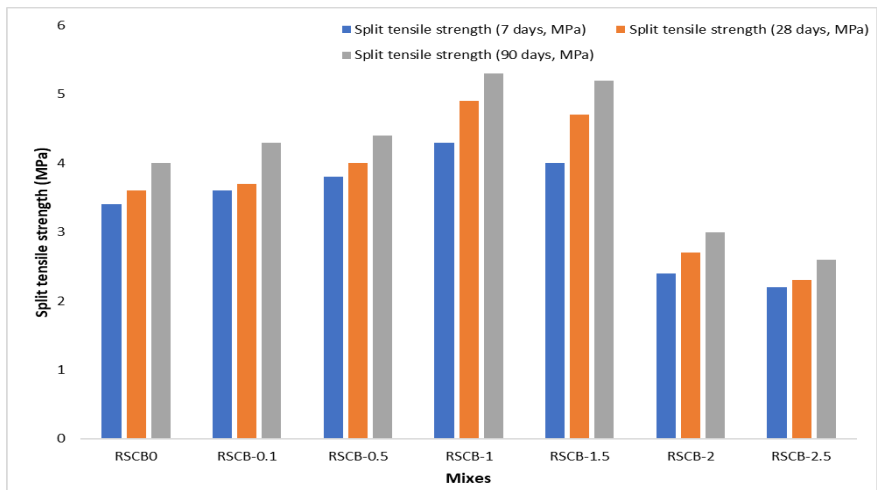


Figure 4: Split tensile strength of the mixes

The role of fibres in these mixes is clearly beneficial—acting as internal bridges that inhibit crack propagation and allow the matrix to carry greater tensile loads before failure. The RSCB-1.5 mix, though slightly less effective than RSCB-1, still maintains relatively high tensile strength. This indicates that the system tolerates a moderate fibre increase beyond the optimal point without drastic compromise. However, a noticeable decline starts with RSCB-2 and becomes more prominent in RSCB-2.5. These reductions in performance suggest that excessive fibre content leads to disruption in uniform fibre distribution, the creation of voids, and impaired compaction, all of which diminish the structural integrity of the hardened geopolymer matrix[3, 37-38]. For sustainable development further research could be enhanced using modern AI and ML [39-43]. Also the techniques like Taguchi and RSM could be used along with for optimizations [44-48].

Conclusion

- Among all the mixes studied, the blend containing 1% basalt fibres (RSCB-1) consistently delivered the most balanced and enhanced performance

across all mechanical properties. It showed notable improvements in compressive, flexural, and tensile strength while maintaining acceptable workability.

- The initial inclusion of basalt fibres in small amounts improved matrix integrity by effectively distributing stress and bridging microcracks. This was evident in the strength gains observed up to the 1% level. Beyond this, however, fibre overloading resulted in poor dispersion and increased internal voids, reducing strength and workability.
- Workability decreased as fibre content increased. The control mix (RSCB0) maintained the highest slump values over time, while the RSCB-2.5 mix showed rapid slump loss. This suggests that higher fibre content leads to reduced flow and stiffening of the fresh mix due to fibre entanglement and increased internal friction.
- All mixes exhibited progressive strength development with time, confirming ongoing geopolymerization even at later ages. The 90-day strength values for RSCB-1 remained the highest, indicating long-term durability potential when optimal fibre content is maintained.
- Excessive fibre content (2% and 2.5%) did not contribute to further mechanical benefits. Instead, it compromised both strength and workability, highlighting the importance of controlling fibre dosage in geopolymer systems.

Overall, a fibre content of 1% by binder weight emerged as the most effective proportion, achieving a strong balance between durability, mechanical performance, and practical workability for geopolymer concrete produced from agro-industrial ashes.

References

- [1] S. Parathi, P. Nagarajan, and S. A. Pallikkara, “Ecofriendly geopolymer concrete: a comprehensive review,” *Clean Technol. Environ. Policy*, vol. 23, no. 6, pp. 1701–1713, Aug. 2021, doi: 10.1007/S10098-021-02085-0.
- [2] J. Davidovits, “Geopolymers and geopolymeric materials,” *J. Therm. Anal.*, vol. 35, no. 2, pp. 429–441, Mar. 1989, doi: 10.1007/BF01904446.
- [3] M. Abbass and G. Singh, “Experimental investigation of alkali-activated hybrid geopolymer concrete,” *Multiscale Multidiscip. Model. Exp. Des.*, vol. 6, no. 2, pp. 235–249, 2023, doi: 10.1007/s41939-023-00144-1.
- [4] M. Abbass and G. Singh, “Experimental investigation of engineered alkali-activated fibrous geopolymer concrete,” *J. Build. Pathol. Rehabil.*, vol. 8, no. 1, pp. 1–16, 2023, doi: 10.1007/s41024-022-00259-x.
- [5] V. K. Popuri, S. K. Kuppala, and B. S. Narayanan, “Cow dung ash (CDA): A sustainable conductive filler for enhancing electromagnetic shielding property of cement mortar,” *Mater. Today Proc.*, 2023, doi: 10.1016/j.matpr.2023.02.020.
- [6] A. Rao, K. N. Jha, and S. Misra, “Use of aggregates from recycled construction and demolition waste in concrete,” *Resour. Conserv. Recycl.*, vol. 50, no. 1, pp. 71–81, Mar. 2007, doi: 10.1016/j.resconrec.2006.05.010.
- [7] Aggarwal, P., Rana, M., Akhai, S.: Briefings on e-waste hazard until COVID era in India. *Mater. Today Proc.* **71**, 389–393 (2022), doi: <https://doi.org/10.1016/j.matpr.2022.09.507>

- [8] M. Abbass and G. Singh, "Impact strength of rice husk ash and basalt fibre based sustainable geopolymer concrete in rigid pavements," *Mater. Today Proc.*, 2021, doi: 10.1016/j.matpr.2021.09.053.
- [9] S. Maruthupandian, "Durability studies on basalt fibre reinforced concrete," *Indian Concr. J.*, vol. 92, no. 4, 2018.
- [10] N. Subramanian *et al.*, "Flexural behaviour of geopolymer concrete beams reinforced with BFRP and GFRP polymer composites," *Adv. Struct. Eng.*, vol. 25, no. 5, pp. 954–965, Apr. 2022, doi: 10.1177/13694332211054229.
- [11] T. Ponikiewski and J. Katzer, "Fresh mix characteristics of self-compacting concrete reinforced by fibre," *Period. Polytech. Civ. Eng.*, vol. 61, no. 2, pp. 226–231, 2017, doi: 10.3311/PPci.9008.
- [12] F. Shaikh and S. Haque, "Behaviour of Carbon and Basalt Fibres Reinforced Fly Ash Geopolymer at Elevated Temperatures," *Int. J. Concr. Struct. Mater.*, vol. 12, no. 1, 2018, doi: 10.1186/s40069-018-0267-2.
- [13] M. Abbass and S. Akhai, "Exploring the sustainability potential of geopolymer concrete with coal bottom ash and basalt fibres," *Multiscale Multidiscip. Model. Exp. Des.*, vol. 8, no. 3, 2025, doi: 10.1007/s41939-025-00794-3.
- [14] M. Abbass and G. Singh, "Optimum Mix Design of Rice Husk Ash-Based Geopolymer Concrete...," *Lect. Notes Civ. Eng.*, vol. 221, pp. 59–74, 2022, doi: 10.1007/978-981-16-8433-3_7.
- [15] N. Aravind *et al.*, "Machine learning model for predicting crack detection...," *Constr. Build. Mater.*, vol. 297, 2021, doi: 10.1016/J.CONBUILDMAT.2021.123785.
- [16] D. R. Kumutha *et al.*, "Experimental Investigation on Properties of Basalt Fiber Reinforced Geopolymer Concrete," *IOSR J. Mech. Civ. Eng.*, vol. 14, no. 3, pp. 105–109, Jun. 2017, doi: 10.9790/1684-140305105109.
- [17] J. Temuujin and B. Darkhijav, "Influence of Basalt Fibres on the Properties of Fly Ash Based," 2016, doi: 10.11629/jpaar.2016.7.1.043.
- [18] M. Abbass *et al.*, "Properties of hybrid geopolymer concrete prepared using rice husk ash, fly ash and GGBS with coconut fiber," *Mater. Today Proc.*, vol. 45, 2021, doi: 10.1016/j.matpr.2021.01.390.
- [19] M. Abbass and G. Singh, "Rice Husk Ash and Basalt Fibre-Based Sustainable Geopolymer Concrete in Rigid Pavements," 2021.
- [20] V. Yadav, S. Singh, M. P. Garg, and S. Akhai, "Effect of natural *Sapindus mukorossi* treatment process on bio-waste bagasse fibers for biocomposite fabrication and application purposes," *Ind. Crops Prod.*, vol. 219, p. 119066, 2024.
- [21] M. Abbass *et al.*, "Properties of Rice Husk Ash and Aluminium Slag-Based Sustainable Geopolymer Bricks," *Lect. Notes Civ. Eng.*, vol. 338, pp. 255–267, 2023, doi: 10.1007/978-981-99-1886-7_22.
- [22] H. Q. Ahmed *et al.*, "Flexural strength... with CFRP bars," *Constr. Build. Mater.*, vol. 231, 2020, doi: 10.1016/j.conbuildmat.2019.117185.
- [23] A. Alsaiif *et al.*, "Fatigue performance of steel fibre reinforced rubberised concrete," *Eng. Struct.*, vol. 193, pp. 170–183, 2019, doi: 10.1016/j.engstruct.2019.05.040.
- [24] M. Kharun and D. Koroteev, "Effect of basalt fibres...," *MATEC Web Conf.*, vol. 251, 2018, doi: 10.1051/mateconf/201825102003.

- [25] M. Abbass and G. Singh, "Durability of rice husk ash and basalt fibre based...", *Mater. Today Proc.*, 2022, doi: 10.1016/j.matpr.2022.02.196.
- [26] T. S. Ng *et al.*, "The behaviour of steel-fibre reinforced geopolymer concrete beams...", *Mag. Concr. Res.*, vol. 65, no. 5, pp. 308–318, Mar. 2013, doi: 10.1680/MACR.12.00081.
- [27] M. K. Ismail and A. A. A. Hassan, "Shear behaviour of rubberized concrete beams...", *Constr. Build. Mater.*, vol. 140, pp. 43–57, 2017, doi: 10.1016/j.conbuildmat.2017.02.109.
- [28] M. Abbass and G. Singh, "Fatigue analysis of rice husk ash and basalt fibre-based...", *Mater. Today Proc.*, 2021, doi: 10.1016/j.matpr.2021.01.450.
- [29] G. B. Maranan *et al.*, "Shear behaviour of geopolymer beams with GFRP spirals," *Compos. Struct.*, vol. 187, pp. 454–465, 2018, doi: 10.1016/J.COMPSTRUCT.2017.12.080.
- [30] T. Alomayri *et al.*, "Thermal and mechanical properties of cotton fabric-reinforced geopolymer composites," *J. Mater. Sci.*, vol. 48, no. 19, pp. 6746–6752, Oct. 2013, doi: 10.1007/S10853-013-7479-2.
- [31] M. Abbass and G. Singh, "Microstructural analysis of environment friendly geopolymer concrete," *Multiscale Multidiscip. Model. Exp. Des.*, 2023, doi: 10.1007/s41939-023-00200-w.
- [32] L. Gao *et al.*, "Eco-friendly basalt fibre concrete by Taguchi method," *Constr. Build. Mater.*, vol. 302, Oct. 2021, doi: 10.1016/j.conbuildmat.2021.124161.
- [33] H. Venu *et al.*, "Fracture toughness in fibrous concrete with low-clinker binder," *Theor. Appl. Fract. Mech.*, vol. 133, 2024, doi: 10.1016/j.tafmec.2024.104641.
- [34] A. Hassan *et al.*, "Effect of curing on fly ash-based geopolymer concrete," *SN Appl. Sci.*, vol. 1, no. 12, 2019, doi: 10.1007/S42452-019-1774-8.
- [35] D. Q. Pham *et al.*, "Structural behaviour of reinforced geopolymer beams," *Structures*, vol. 33, pp. 567–580, 2021, doi: 10.1016/J.ISTRUC.2021.04.077.
- [36] M. Łach *et al.*, "Mechanical Properties of Waste Tire Cords Reinforced Geopolymer Concretes," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 416, 2018, doi: 10.1088/1757-899X/416/1/012089.
- [37] A. J. Daniel *et al.*, "Hybrid fibre geopolymer under cyclic loading," *Procedia Eng.*, vol. 173, pp. 417–423, 2017, doi: 10.1016/J.PROENG.2016.12.041.
- [38] K. H. Mo *et al.*, "Shear and mechanical properties of steel fibre geopolymer concrete," *Constr. Build. Mater.*, vol. 148, pp. 369–375, Sep. 2017, doi: 10.1016/j.conbuildmat.2017.05.017.
- [39] S. Akhai and M. Abbass, "Toward Resilient Futures: The Role of AI-Driven Strategies in Climate Adaptation," in *Nexus of AI, Climatology, and Urbanism for Smart Cities*, IGI Global Scientific Publishing, 2025, pp. 325–340.
- [40] M. Abbas, S. Akhai, U. Abbas, R. Jafri, and S. M. Arif, "AI-enabled sustainable urban planning and management," in *Real-World Applications of AI Innovation*, IGI Global Scientific Publishing, 2025, pp. 233–260.
- [41] M. Abbass, U. Abbas, R. Jafri, S. M. Arif, and S. Akhai, "AI and machine learning applications in sustainable smart cities," in *Sustainable Smart Cities and the Future of Urban Development*, IGI Global Scientific Publishing, 2025, pp. 1–32.

- [42] M. Abbass *et al.*, “Disaster Risk Reduction and Management With Emerging Technologies,” in *Revolutionizing Urban Development and Governance With Emerging Technologies*, IGI Global, 2025, pp. 71–110.
- [43] A. S. Wadhwa and M. Abbass, “Integrating Taguchi optimization for multi-criteria decision-making,” in *Recent Theories and Applications for Multi-Criteria Decision-Making*, IGI Global Scientific Publishing, 2024, pp. 125–150.
- [44] A. S. Wadhwa, S. Akhai, M. Abbass, A. Chouksey, S. Tiwari, and T. Taneja, “Computational intelligence-driven design and optimization of polyurethane belt-type oil skimmer for sustainable manufacturing using SolidWorks 3D CAD,” in *Using Computational Intelligence for Sustainable Manufacturing of Advanced Materials*, IGI Global Scientific Publishing, 2025, pp. 445–464.
- [45] H. Kumar, A. S. Wadhwa, S. Akhai, and A. Kaushik, “Parametric analysis, modeling and optimization of the process parameters in electric discharge machining of aluminium metal matrix composite,” *Eng. Res. Express*, vol. 6, no. 2, p. 025542, 2024.
- [46] H. Kumar, A. S. Wadhwa, S. Akhai, and A. Kaushik, “Parametric optimization of the machining performance of Al-SiCp composite using combination of response surface methodology and desirability function,” *Eng. Res. Express*, vol. 6, no. 2, p. 025505, 2024.
- [47] S. Akhai, “Navigating the potential applications and challenges of intelligent and sustainable manufacturing for a greener future,” *Evergreen*, vol. 10, no. 4, pp. 2237–2243, 2023.
- [48] S. Akhai, “A review on optimizations in μ -EDM machining of the biomedical material Ti6Al4V using the Taguchi method: Recent advances since 2020,” *Latest Trends in Engineering and Technology*, pp. 395–402, 2024.

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