International Journal of Advanced Technology and Engineering Exploration, Vol 12(131)
ISSN (Print): 2394-5443 ISSN (Online): 2394-7454
http://dx.doi.org/10.19101/IJATEE.2024.111101717

Research Article

Bond–slip analysis of basalt fiber-reinforced concrete incorporating rice husk ash and nano rice husk ash under impact loading

Saravanan MM[1*], Ananthakumar Ayyadurai[1], Dineshkumar G[2] and Sivaraja M[3]
Associate Professor, Department of Civil Engineering, Vivekanandha College of Engineering for Women, Tiruchengode, Tamilnadu, India[1]
Associate Professor, Department of Civil Engineering, Vaagdevi College of Engineering, Telengana, India[2]
Professor, Department of Civil Engineering, Nehru Institute of Technology, Kaliyapuram, Coimbatore, Tamilnadu, India[3]

Received: 20-September-2024; Revised: 06-October-2025; Accepted: 08-October-2025
©2025 Saravanan MM et al. This is an open access article distributed under the Creative Commons Attribution (CC BY) License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract
Recent research has been conducted to investigate the dynamic behavior of fiber-reinforced concrete (FRC) under impact loading conditions. This study focuses on examining the structural response of basalt fiber–reinforced concrete (BFRC) incorporating rice husk ash (RHA) and nano rice husk ash (nRHA) when subjected to impact forces. The findings highlight the critical influence of fiber failure modes, particularly under dynamic impact conditions. The study introduces a range of concrete mixtures with varying combinations of RHA and nRHA, along with different proportions of basalt fiber. Rather than completely replacing ordinary Portland cement (OPC), micro-particle RHA and nRHA were partially substituted at varying percentages (5%, 10%, 15%, 20%, 25%, and 30%). All mixtures included a constant 0.5% volume fraction of basalt fiber. These combinations were systematically evaluated to assess their impact resistance, providing insights into the synergistic interaction among these materials. The experimental results indicate that the mixtures containing 15% RHA with 0.50% basalt fiber and 20% nRHA with 0.50% basalt fiber demonstrated the highest toughness under impact loading conditions. This finding emphasizes the importance of optimizing BFRC composition with RHA and nRHA to enhance its structural performance in dynamic loading environments.

Keywords
Basalt fiber–reinforced concrete, Rice husk ash, Nano rice husk ash, Impact loading, Toughness, Dynamic behavior.

1.Introduction
Research on the dynamic behaviour of fiber-reinforced concrete (FRC) under varied loading situations, especially its performance under impact pressures, has significantly increased in recent years. This study investigates the structural response of basalt fiber reinforced concrete (BFRC) elements under impact loading with the incorporation of two additional materials: rice husk ash (RHA) and nano rice husk ash (nRHA). The main objectives of this study are to clarify how these materials influence the mechanical properties of BFRC and to evaluate their suitability for environments subjected to sudden dynamic forces.

The nonlinear response of concrete elements under impact loading, emphasizing the importance of material enhancements for improving impact resistance. The potential of RHA and nRHA to enhance the toughness and durability of BFRC, particularly under flexural stress, offers valuable insights into the application of sustainable materials for improving concrete performance under dynamic loading conditions [1]. Furthermore, the modification of the American Concrete Institute (ACI) drop-weight impact test for concrete enhances the accuracy and relevance of impact resistance evaluation, providing a critical framework for assessing the improved toughness and durability of BFRC incorporating RHA and nRHA, especially in terms of flexural behavior [2]. The influence of steel and polypropylene fibers on the impact resistance of FRC has been extensively investigated using both experimental and numerical methods, highlighting the significant role that different fiber types play in

*Author for correspondence

enhancing concrete's impact resistance [3]. Studies on concrete pavements reinforced with recycled steel fibers obtained from post-consumer tires have demonstrated improved fatigue resistance and cracking behavior, contributing to the sustainability and enhanced durability of FRC [4]. Moreover, the inclusion of nRHA, a nanoscale material, has been shown to improve the mechanical properties and durability of BFRC, particularly under flexural and dynamic loading conditions [5]. Basalt fibers, when combined with RHA and nRHA, can enhance the toughness, strength, and ductility of BFRC, particularly under flexural loading, offering insights into optimizing concrete performance with sustainable additives [6]. Incorporating basalt fibers along with RHA and nRHA can improve the flexural toughness of BFRC, addressing both sustainability and performance in concrete subjected to dynamic and static loads [7]. The inclusion of nRHA, a nano scale material, along with basalt fibers, can improve the flexural toughness and overall durability of BFRC, particularly under dynamic loading conditions. RHA and nRHA can enhance the mechanical properties and toughness of BFRC, particularly under flexural stress, by leveraging the benefits of these materials at both micro and nano scale [8, 9]. Integration of RHA and nRHA, alongside basalt fibers, can improve the mechanical properties and toughness of BFRC, particularly in the context of dynamic and flexural loading conditions [10–12]. Benefits of nanoscale additives to improve concrete performance under dynamic and flexural loads [13]. The type of reinforcement significantly influences the impact resistance of concrete. Similarly, basalt fibers, combined with RHA and nRHA, enhance the flexural toughness of BFRC, particularly focusing on its performance under dynamic and flexural stresses [14, 15].

Concrete's durability under dynamic loading is limited by its low tensile strength, quick fracture propagation, insufficient energy absorption, and post-crack performance, all of which contribute to brittle failure when exposed to impact loads [16, 17]. It is difficult to achieve uniform dispersion and strong bonding inside the matrix, even though basalt fibres can increase hardness [18]. RHA and nRHA are examples of supplemental materials that might improve mechanical characteristics and microstructure, but they may also weaken the interfacial transition zone (ITZ) and decrease workability [19, 20]. By employing the reinforcing properties of basalt fibres in conjunction with RHA and nRHA, this work develops a hybrid mix that enhances bond-slip behaviour and impact resistance.

The primary objectives of this research align with the chosen methodology, ensuring a focused and effective investigation into the structural response of BFRC incorporating RHA and nRHA under impact loading. This study evaluates the flexural toughness of BFRC with varying proportions of RHA, nRHA, and basalt fiber content under dynamic loading conditions to identify the optimal mixture demonstrating superior flexural performance. X-ray diffraction (XRD) analysis was conducted to examine structural changes and mineral composition. Comparisons with conventional concrete (CC) highlight the significant improvements in structural performance achieved through the integration of RHA and nRHA.

From the reviewed literature, it is evident that incorporating fibers and supplementary cementitious materials significantly enhances the impact resistance and flexural toughness of concrete. However, most existing studies have focused on conventional fibers such as steel and polypropylene, with limited exploration of basalt fibers combined with RHA and nRHA ash under dynamic loading. Moreover, the bond–slip response and micro-structural mechanisms governing the improved performance of such hybrid composites remain insufficiently understood. Therefore, the present study aims to bridge these gaps by comprehensively investigating the bond–slip behavior and impact performance of BFRC incorporating RHA and nRHA.

The paper is organized as follows: Section 2 presents a comprehensive review and analysis of the literature on BFRC and the incorporation of RHA and nRHA. Section 3 details the experimental methodology. Section 4 discusses the results and key findings of the study. Finally, Section 5 concludes the paper and highlights potential directions for future research.

2.Related work

Research on FRC has increasingly focused on integrating mineral and nano-scale admixtures to improve its response under impact loading. Experimental studies employing methods such as drop-weight impact testing, pull-out bond–slip analysis, and tensile strength evaluation show that fibers significantly enhance energy absorption and crack resistance, while supplementary binders like RHA and nRHA contribute to microstructural densification and stronger ITZs. These effects are

particularly evident when moderate RHA replacement levels (10–20%) are combined with basalt or other fibers, leading to greater impact toughness and improved bond characteristics. The advantages of such blends include increased durability, reduced dependency on ordinary Portland cement (OPC), and alignment with sustainable construction practices through the utilization of agricultural waste. Nonetheless, limitations such as early-age strength reduction at higher replacement levels, challenges in achieving uniform dispersion of nano-particles, and added material costs restrict broader application.

This literature review presents a comprehensive examination of recent advancements aimed at enhancing the impact resistance of concrete structures. It covers both conventional methods and emerging innovations, focusing on strategies that improve performance and promote sustainability [21–25]. Traditional approaches, such as using lightweight insulating plaster for improved fire endurance and engineered cementitious composites (ECC) incorporating industrial by-products, are discussed for their contributions to structural resilience and environmental benefits [26–28]. A significant emphasis is placed on the role of fibers in strengthening concrete against impact loads [29, 30]. Research on steel and basalt fiber-reinforced composites consistently demonstrates their effectiveness in increasing toughness and energy absorption. The use of recycled steel fibers, particularly those recovered from waste tires, are highlighted as a sustainable solution that also enhances durability.

The review also explores the growing influence of nanotechnology in concrete innovation. Studies on silica nano particles and nano-SiO2 illustrate their potential to refine the microstructure of cementitious materials, resulting in improved mechanical properties and durability [31]. Additionally, RHA is identified as a promising sustainable additive capable of enhancing both strength and long-term performance when used as a partial cement replacement [32–35].

Understanding the complex behavior of concrete under impact loading is presented as a critical area of research. Several studies have developed innovative assessment techniques and investigated the interaction between fiber characteristics and matrix composition in high-strength FRC [36–39]. Throughout the review, there is a consistent emphasis on sustainability, demonstrated using recycled materials such as steel fibers and waste copper, along with bio-based additives like RHA. The overall research methodology, including problem identification, material collection, mix proportioning, testing, and result analysis, is clearly illustrated in *Figure 1.*

A combination of previous research findings and preliminary trial mixes conducted at the outset of this study guided the selection of replacement levels for RHA and nRHA, which ranged from 5% to 30% [12, 15]. Earlier studies have demonstrated that RHA possesses significant pozzolanic activity and can improve the strength and durability of concrete when incorporated at replacement levels typically between 5% and 25% by weight of cement [18, 19]. Higher replacement levels, up to 30%, have also been investigated in several studies, with performance outcomes varying according to mix design parameters, particle fineness, and curing conditions [25, 28].

To determine the threshold at which dilution of the cementitious content begins to adversely affect mechanical performance—particularly flexural toughness—an upper replacement limit of 30% was selected. Owing to its high reactivity and ultrafine particle size, nano RHA has commonly been reported in previous studies at lower replacement levels, typically ranging from 2% to 10% [12, 19]. However, to comprehensively assess its synergistic interaction with basalt fibers and to establish practical limits for both workability and mechanical performance, the replacement range was extended up to 30% in the present study.

Based on previous research, a fixed 0.5% volume fraction of basalt fibers was selected, as it provides an optimal balance between workable consistency and mechanical enhancement particularly in terms of flexural toughness and post-cracking behavior—without requiring excessive admixture dosage [29]. Furthermore, preliminary trial mixes confirmed that the concrete retained adequate castability at 0.5% fiber content when used with a moderate amount of superplasticizer, while demonstrating notable improvements in toughness and fracture resistance.

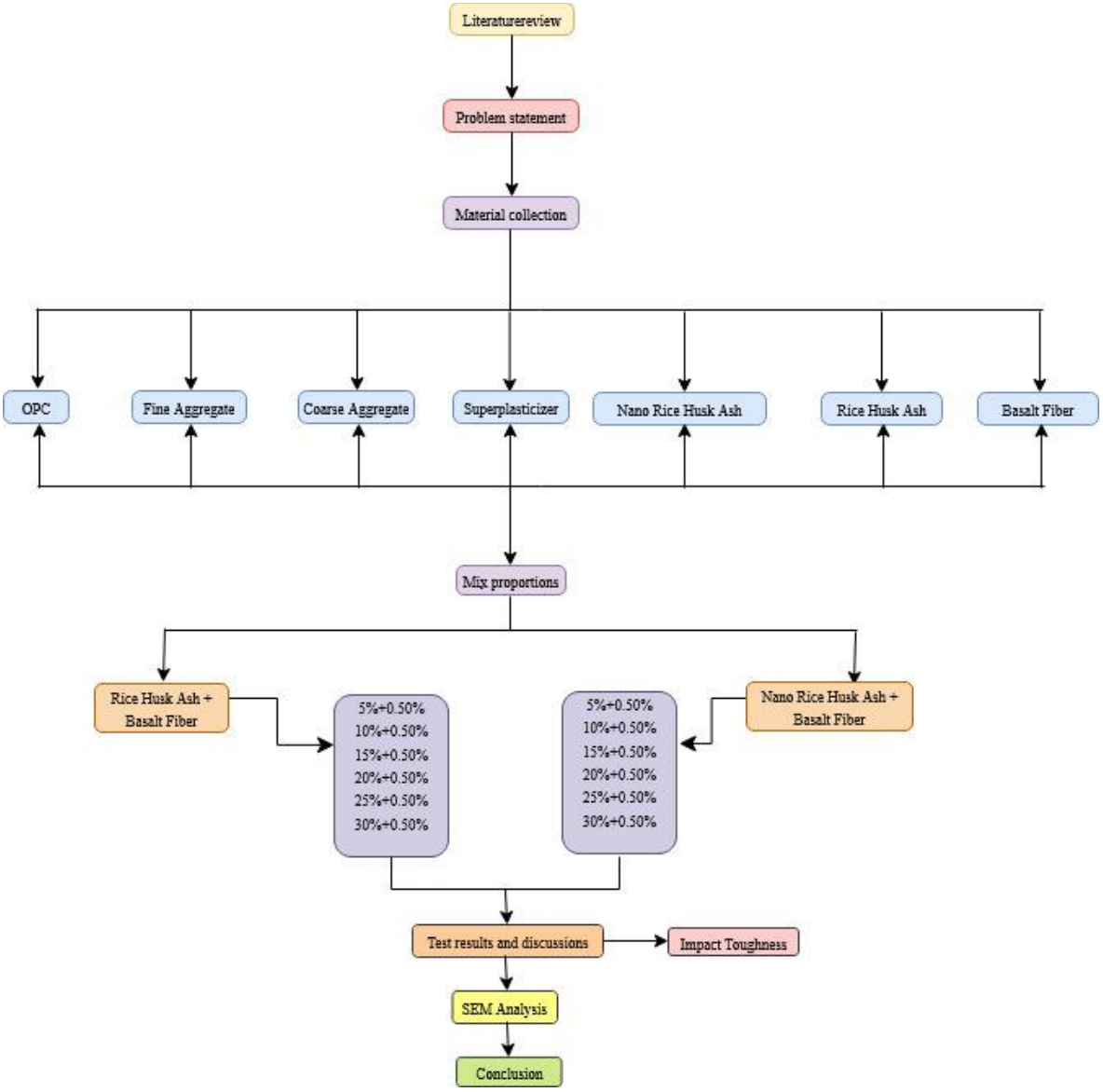


Figure 1 Research methodology

3.Material and methods

3.1Cement

Cement, a vital component of concrete, plays a decisive role in determining its mechanical and physical properties. In this study, OPC of 53 Grade was utilized. The specific gravity of the cement, a key parameter influencing its performance in concrete, was found to be 3.15. All testing procedures were conducted in accordance with the guidelines specified in IS: 4031 – 1988. The determination of specific gravity provides valuable insight into the cement's density and volumetric characteristics. The use of OPC 53 Grade ensures material consistency and facilitates reproducibility in future studies. A concise summary of the test results is presented in *Table 1.*

Table 1 Physical properties of cement

Test Particulars	Test Results
Fineness (%)	6
Normal consistency (%)	31
Initial setting time (min)	35
Final setting time (min)	320
Soundness (mm)	2.86
Compressive strength (CS) (MPa) 3-days	30.80
CS (MPa) 7-days	38.50
CS (MPa) 28-days	54.60

3.2Fine aggregate

In this study, commercially available river sand served as the fine aggregate in the concrete mixtures. To ensure uniformity, the sand underwent sieving, adhering to the IS: 2386 - 1963 testing procedure. The sieving process involved passing the sand through a 4.75 mm sieve while retaining it with a 150-micron sieve. The river sand demonstrated a fineness modulus of 2.86 and a specific gravity of 2.65.

The particle size distribution results, presented in *Figure 2*, conform to the grading zone III specifications of IS: 383-1970. This standardized testing procedure enhances reproducibility for other researchers aiming to replicate or further investigate the impact of fine aggregate characteristics on concrete properties. The clear depiction of particle size distribution aids in visualizing the granular composition, offering valuable insights for future studies in concrete material science.

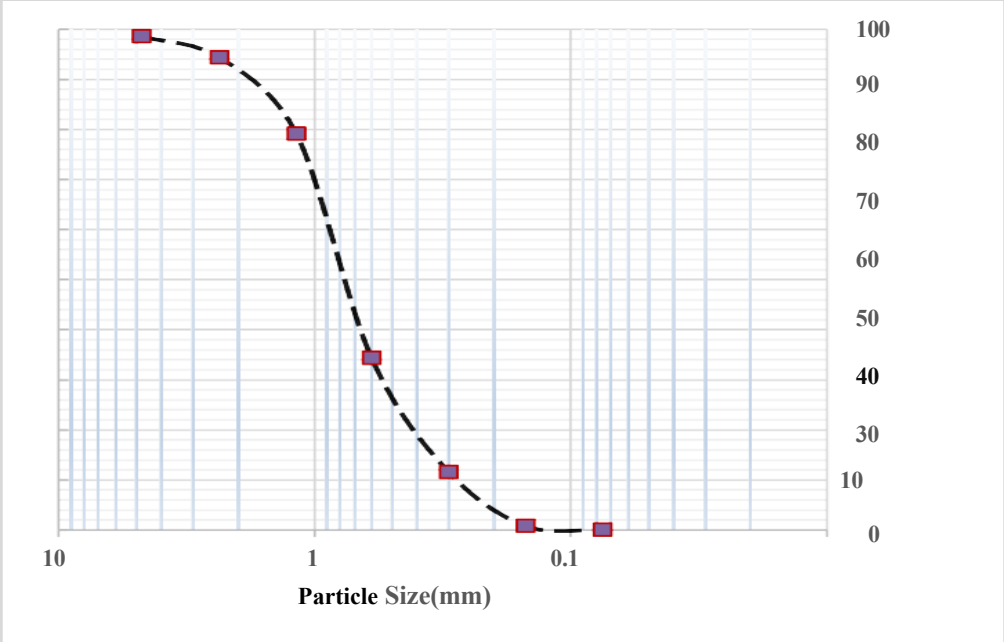


Figure 2 Particle size distribution of fine aggregate

3.3Coarse aggregate

Coarse aggregate, constituting 70–80% of the total concrete volume and forming the primary structural matrix, was procured from a local quarry. The collected crushed stone aggregates were angular and nearly uniform in size, with a nominal diameter of 20 mm. Testing of the coarse aggregates was conducted in accordance with IS: 2386 (Part I–IV) – 1963. The specific gravity of the coarse aggregate, a critical property influencing mix design and strength characteristics, was determined to be 2.74, complying with the requirements specified in IS: 383 – 1970.

3.4Superplasticizer

Superplasticizers, essential for improving the workability of concrete, were utilized in this study. The chosen plasticizer was naphthalene-based, and it complied with IS 9103-1999, BS: 5075 Part 3, and American Society for Testing and Materials (ASTM) C - 494 standards. Due to practical constraints, specific laboratory tests for superplasticizers were not conducted. The manufacturer's specifications for the superplasticizer are detailed in *Table 2*. Researchers aiming to reproduce or build upon this study can refer to this table for essential properties and dosage recommendations, ensuring consistency and comparability in subsequent investigations.

Table 2 Properties of superplasticizer

Properties	Test results (Manufacturer)
Type	Sulphonated Naphthalene Formaldehyde Condensate
Specific gravity	1.220 to1.225 at 30^0C
Chloride content	Nil as per IS: 456:2000 and BS:5075
Recommended dosage	0.6-1.5liters per100kg of cement
Approximate additional air entrainment	1% at normal dosages
Solid content	40%

Properties	Test results (Manufacturer)
CS	Early strength up to 40% - 50%
Durability	Good

3.5RHA and nRHA

RHA, a key supplementary cementitious material, was produced by subjecting rice husks to a 48-hour open combustion process. The resulting grey-colored ash was subsequently processed in a ball mill following the Box–Behnken method, yielding micro-sized RHA particles. Furthermore, nano RHA (nRHA) was produced by extended grinding of rice husks in a ball mill, resulting in particles significantly finer than those of conventional RHA (*Table 3*).

The reproducibility of this procedure is facilitated by the clarity in describing the ash production methods and the distinct characteristics of RHA and NRHA. Researchers can utilize this information to reproduce the same ash types for comparative studies and further exploration in concrete material development.

The specific surface area of the nRHA was determined using Brunauer–Emmett–Teller (BET) surface area analysis. The results indicated a highly reactive surface suitable for enhanced pozzolanic activity, with a BET surface area of approximately 67.4 m^2/g. This increased surface area contributes to improved mechanical strength and durability of concrete—particularly under impact and flexural loading conditions—by reinforcing the bonding within the cementitious matrix and facilitating the nucleation of additional calcium silicate hydrate (C–S–H) gels.

Table 3 Chemical Composition of RHA and nRHA

Material	Losson ignition%	SiO2%	CaO%	MgO%	Fe2O3%	Al2O3%	Na2O%	K2O%
RHA	7.27	82.89	0.76	0.97	0.53	1.68	0.20	--
NRHA	0.69	90.48	1.22	1.56	0.72	3.40	0.31	--

3.6Basalt fiber

Basalt fiber used in this study consists of natural basalt chopped strands derived from volcanic rock sources. These fibers exhibit superior tensile strength owing to their volcanic origin. Although specific fiber tests were not performed in the laboratory, the material properties were obtained directly from the manufacturer and are summarized in *Table 4.*

Table 4 Properties of basalt fiber

S. No.	Property	Values
1	Diameter (mm)	0.013
2	Cut length (mm)	16.0
3	Aspect ratio	1230
4	Density (g/cm^3)	2.65
5	Tensile strength (MPa)	4150

This concise description provides a clear understanding of the basalt fiber characteristics used in the study. By presenting information directly obtained from the manufacturer, the methodology ensures reproducibility for future studies seeking to incorporate similar fibers in concrete investigations.

3.7Mix proportion and identification

The research involved experimenting with various concrete mixes, each designed with different proportions to optimize the overall composition. OPC was partially replaced with microparticle RHA and nRHA at replacement levels of 5%, 10%, 15%, 20%, 25%, and 30%. In all mixes, a constant volume fraction of 0.5% basalt fiber was incorporated. The mixes were designated as reinforced beam (RB1) to RB6 and nano reinforced beam (NRB1) to NRB6, representing varying levels of cement replacement with RHA and nRHA, respectively, along with the inclusion of basalt fiber.

RB1 denotes a 5% replacement of cement with RHA along with the addition of 0.5% basalt fiber. RB2 corresponds to a 10% cement replacement with RHA and 0.5% basalt fiber, continuing sequentially up to RB6, which represents a 30% replacement. Similarly, NRB1 indicates a 5% replacement of cement with nRHA and 0.5% basalt fiber, while NRB2 to NRB6 represent progressively higher replacement levels with nRHA, maintaining the same basalt fiber content.

Throughout the study, the superplasticizer content was maintained at a constant 1%, consistent with the fixed volume fraction of fiber. This approach ensures the reproducibility of mix proportions and facilitates their adoption by other researchers investigating similar concrete compositions (*Table 5*).

Table 5 Mix proportions for RHA and nRHA mixes

Mix ID	Cement (kg)	FA (kg)	CA (kg)	RHA (kg)	NRHA (kg)	Basalt (%)	Water content(lit)	Super plasticizer (%)
CC	350	717	1356	0	--	0	140	0
RB1	332.5	717	1356	17.5	--	0.50	140	1
RB2	315	717	1356	35	--	0.50	140	1
RB3	297.5	717	1356	52.5	--	0.50	140	1
RB4	280	717	1356	70	--	0.50	140	1
RB5	262.5	717	1356	87.5	--	0.50	140	1
RB6	245	717	1356	105	--	0.50	140	1
NRB1	332.5	717	1356	--	17.5	0.50	140	1
NRB2	315	717	1356	--	35	0.50	140	1
NRB3	297.5	717	1356	--	52.5	0.50	140	1
NRB4	280	717	1356	--	70	0.50	140	1
NRB5	262.5	717	1356	--	87.5	0.50	140	1
NRB6	245	717	1356	--	105	0.50	140	1

3.8 Workability

Although the mechanical properties of BFRC incorporating RHA and nRHA were the primary focus of this study, evaluating the workability of each mix was equally essential to ensure practical applicability. To assess the fresh concrete behavior, slump tests were performed for all mixes in accordance with ASTM C143. In cases where the mix contained a high proportion of fine particles, particularly with nRHA, flow table tests were additionally conducted to provide better characterization, especially when the slump values were very low.

Table 6 Slump values of RHA and nRHA mixes

Mix ID	RHA (kg)	nRHA (kg)	Basalt (%)	Slump value (mm)
CC	0	--	0	85
RB1	17.5	--	0.50	95
RB2	35	--	0.50	92
RB3	52.5	--	0.50	85
RB4	70	--	0.50	78
RB5	87.5	--	0.50	75
RB6	105	--	0.50	72
NRB1	--	17.5	0.50	98
NRB2	--	35	0.50	95
NRB3	--	52.5	0.50	90
NRB4	--	70	0.50	88
NRB5	--	87.5	0.50	85
NRB6	--	105	0.50	75

The results indicated a noticeable reduction in workability with increasing fiber content and higher levels of cement replacement using RHA and nRHA. The control mix (without fibers or supplementary materials) exhibited a slump of 85 mm, reflecting moderate workability. However, with the incorporation of basalt fibers (0.5% by volume), the slump values dropped significantly—often below 80 mm—due to increased internal friction among fibers and a reduction in free water within the mix (*Table 6*). Similarly, the inclusion of RHA, and more prominently nRHA, further decreased workability. RHA, owing to its porous and angular morphology, increased the water demand, while nRHA, characterized by its ultrafine particle size and higher surface area, required additional water for proper dispersion and hydration. In mixes containing both fibers and nRHA, the combined effect often necessitated the use of a superplasticizer to achieve a workable consistency.

3.9Density and air content

Both the fresh and hardened densities of the concrete mixtures were evaluated to obtain a comprehensive understanding of their physical properties. The bulk density of fresh concrete was determined using the unit weight method in accordance with ASTM C138/C138M. The control mix exhibited a fresh density of approximately 2400 kg/m^3, whereas mixes incorporating RHA and nRHA showed slightly lower

densities, ranging from 2280 to 2350 kg/m³, depending on the replacement level. This reduction can be attributed to the lower specific gravities of RHA and nRHA compared with OPC.

The density of hardened concrete was measured after 28 days following ASTM C642. The results revealed that hardened densities ranged between 2250 and 2370 kg/m³ across all mixtures, following a similar trend. Slightly lower densities were more prominent in mixes with higher proportions of RHA/nRHA, primarily due to the pozzolanic materials' reduced mass and increased porosity.

In parallel, the air content of fresh concrete was assessed using the pressure method as per ASTM C231/C231M. The control mix exhibited an air content of about 1.8%, while mixes containing fibers and pozzolanic materials showed an increase to 2.5–3.2%, particularly at higher replacement levels of RHA/nRHA. This rise can be attributed to the finer particles' higher surface area and reduced workability, which promoted air entrapment within the mix.

3.10Curing method

All concrete specimens were cured using the standard water-curing method to ensure uniform and complete hydration—an aspect particularly crucial for mixes containing pozzolanic materials such as RHA and nRHA. The specimens were demolded after 24 hours and immediately immersed in a water-curing tank to prevent moisture loss and promote proper strength development. The curing period was maintained for 28 days to allow sufficient time for the pozzolanic reaction of RHA and nRHA to effectively contribute to the mechanical properties of the concrete.

The curing temperature was carefully controlled and maintained at 27 ± 2 °C throughout the 28-day period, providing optimal conditions for both cement hydration and pozzolanic activity in accordance with standard practices. Daily monitoring was performed to ensure consistency of the curing environment and to minimize the risk of premature cracking or inadequate hydration. This controlled curing regime was essential to achieve reliable and uniform performance across all mix variations.

4.Results and discussion

4.1Impact toughness

Concrete slab specimens measuring 600 mm × 600 mm × 60 mm were carefully cast and prepared to evaluate impact toughness. The impact tests simulated real loading conditions by allowing a 5.74 kg steel weight to freely fall from a height of 1.6 meters onto the center of the slab, thereby producing a concentrated impact. All tests were performed using a modified version of the ACI 544.2R-89 drop-weight impact test, adapted for slab specimens instead of cylindrical ones. This modification enabled a more accurate representation of real-world structural behavior under localized dynamic loading. Each concrete mix was tested in triplicate to ensure statistical reliability. The impact energy absorbed was quantified at two critical stages: the initiation of the first visible surface crack and the point of final crack propagation leading to failure. All mixes contained 0.5% basalt fiber by volume, with varying levels of cement replacement using RHA and nRHA. The results, illustrated in *Figure 3*, demonstrate variations in the energy absorption capacities among the different mixes. Overall, the findings indicate that the combined incorporation of pozzolanic materials (RHA/nRHA) and basalt fibers enhances the impact resistance of concrete slabs.



Figure 3 Impact strength test setup

4.2Impact toughness behavior of RHA concrete with basalt fiber

The investigation into the behavior of RHA concrete with the incorporation of basalt fiber has revealed profound improvements in the material's impact resistance. In contrast to CC, which exhibits yielding and initiates cracks upon the first impact, ultimately leading to complete failure with subsequent blows, the RHA concrete specimens presented a remarkable enhancement in toughness.

The baseline toughness of the CC slab was measured at 90.092 Nm. Through meticulous impact toughness testing in the laboratory, a substantial increase in both first crack toughness and ultimate toughness was observed in RB1, RB2, and RB4 specimens compared to CC. Specifically, the first crack toughness of these RHA concrete slabs was three times greater, while the ultimate toughness exhibited a remarkable fivefold increase in comparison to CC slabs.

Figure 4 illustrates the variations in first-crack toughness and ultimate toughness among the six RHA concrete specimens. Among them, mix RB3 exhibited the most superior performance, demonstrating exceptional results in both parameters. This mix, incorporating 15% cement replacement with RHA and 0.50% basalt fiber, outperformed CC by approximately four times in first-crack toughness and showed an impressive sixfold enhancement in ultimate toughness.

Table 7 compelling results highlight the significant potential of integrating RHA and basalt fibers as effective additives in concrete formulations. The observed improvements not only enhance impact and crack resistance but also contribute to the long-term structural integrity of concrete. Furthermore, this research paves the way for future studies aimed at refining such composite systems, advancing the development of sustainable and resilient construction materials for next-generation infrastructure applications.

Table 7 Values of first crack and ultimate toughness

Mix ID	RHA (kg)	nRHA (kg)	Basalt (%)	ϕ_{fc}	ϕ_u
CC	0	--	0	90.092	90.092
RB1	17.5	--	0.50	270.288	450.48
RB2	35	--	0.50	270.288	450.48
RB3	52.5	--	0.50	360.384	560.576
RB4	70	--	0.50	270.288	450.48
RB5	87.5	--	0.50	180.192	340.84
RB6	105	--	0.50	180.192	340.84

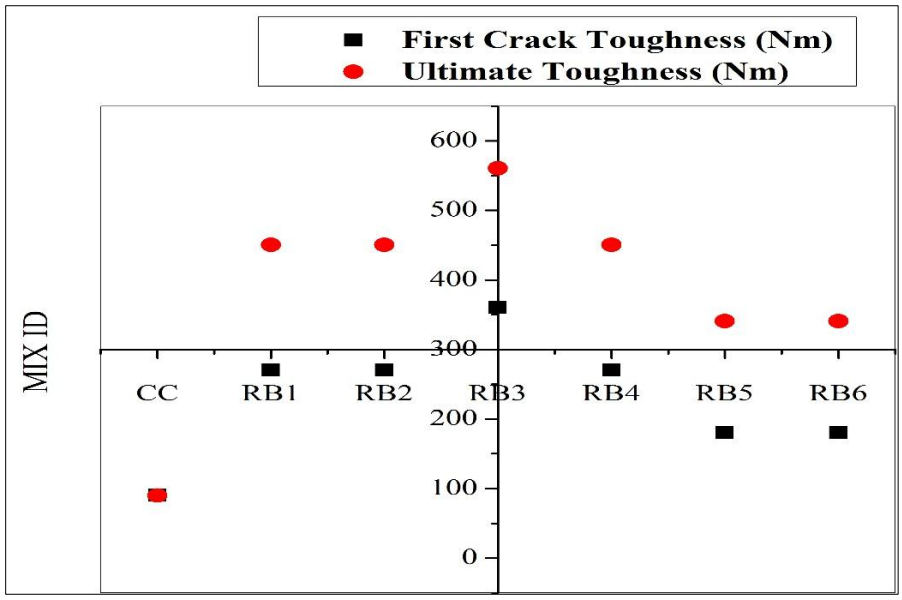


Figure 4 Impact toughness of RHA with basalt fiber

In *Figure 5*, a significant correlation between the first crack toughness (ϕ_{fc}) and ultimate toughness(ϕ_u) (Equation 1) of RHA with basalt fiber is evident. This correlation is described by the following empirical relationship:

$$\phi_u = (1.648 * \phi_{fc}) + 1.394 \quad (1)$$

$R^2 = 0.937$

Where, ϕ_u-ultimate toughness (Nm), ϕ_{fc}- first crack toughness (Nm)

The coefficient of determination (R^2) for this relationship is calculated to be 0.937, indicating a strong and positive association between these two important mechanical properties. This finding suggests that as the first crack toughness increases, there is a corresponding increase in ultimate toughness, which is a critical factor in assessing the material's resistance to fracture and its overall durability.

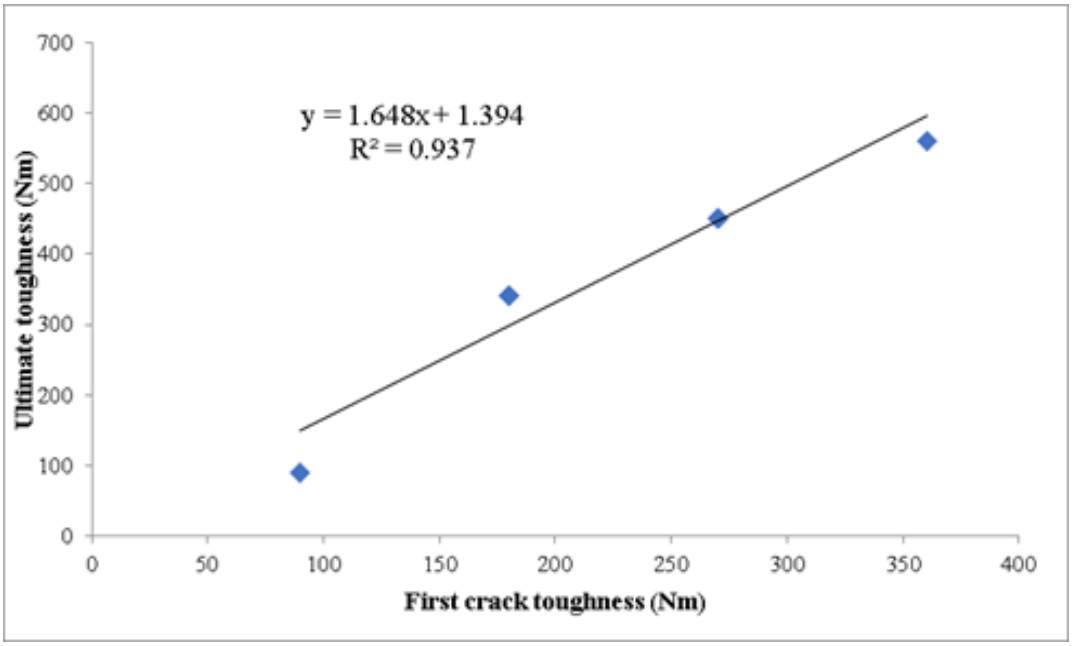


Figure 5 Relationships between first crack toughness and ultimate toughness of RHA with basalt fiber

4.3Impact toughness behavior of nRHA concrete with basalt fiber

The examination of nRHA concrete specimens, like the study conducted on RHA concrete, provided valuable insights into the first-crack and ultimate toughness in comparison with conventional concrete slabs in *Table 8*. Notably, in terms of first-crack toughness, specimens NRB5 and NRB6 exhibited performance comparable to that of conventional concrete, while their ultimate toughness values were approximately twice as high. *Figure 6* illustrates the variations observed in the first-crack and ultimate toughness of nRHA-based concrete specimens.

Table 8 Vaues of first crack and ultimate toughness

Mix ID	RHA (kg)	nRHA (kg)	Basalt (%)	ϕ_{fc}	ϕ_u
CC	0	--	0	90.092	90.092
NRB1	--	17.5	0.50	180.192	360.384
NRB2	--	35	0.50	360.384	630.672
NRB3	--	52.5	0.50	360.384	720.768
NRB4	--	70	0.50	450.48	810.864
NRB5	--	87.5	0.50	270.288	540.576
NRB6	--	105	0.50	270.288	540.576

Among the nRHA concrete mixes, specimens NRB2 and NRB3 achieved a first-crack toughness of 360.384 Nm. Furthermore, NRB2, NRB3, and NRB4 exhibited superior performance compared to the remaining mixes. Particularly noteworthy was the performance of NRB4, which incorporated a 20% replacement of cement with nRHA. This mix demonstrated a fivefold improvement in first-crack toughness and an impressive ninefold increase in ultimate impact toughness compared to conventional slab specimens. However, it is worth noting that the RHA mix with 15% cement replacement outperformed the corresponding nRHA specimen.

A critical observation emerges when comparing RHA with 15% cement replacement and nRHA-based

concrete. The results indicate that RHA may provide better impact toughness performance than its nano counterpart. These nuanced findings highlight the complex influence of nano-sized particles on concrete properties, underscoring the importance of careful material selection in concrete formulation and design.

The significance of these results extends to the potential optimization of concrete mixtures for enhanced impact resistance, a crucial consideration in diverse construction and infrastructure applications. Further exploration and fine-tuning of these materials and their proportions hold promise for the development of tailored concrete solutions that not only meet but exceed the requirements for impact resilience in real-world applications. This research sets the stage for continued advancements in concrete technology, offering a pathway to more resilient and durable construction materials.

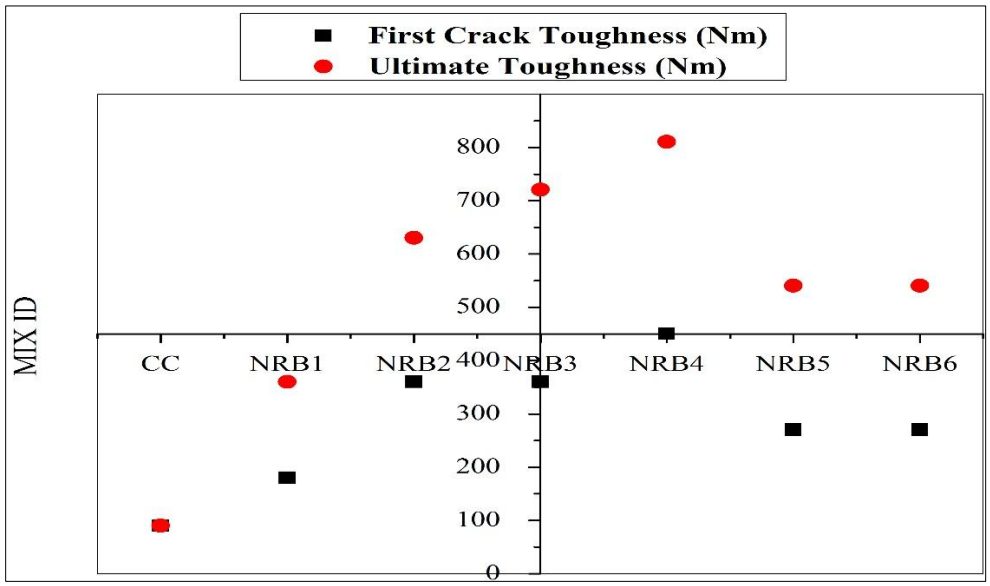


Figure 6 Impact toughness of nRHA with basalt fiber

In *Figure 7,* a compelling and robust relationship has been established between two crucial mechanical properties of nRHA with basalt fiber composite materials: the first crack toughness (ϕ_{fc}) and ultimate toughness (ϕ_u) (Equation 2). The empirical equation describing this relationship is expressed as follows:

$$\phi_u = (1.947 * \phi_{fc}) + 23.70 \quad (2)$$

$R^2 = 0.960$

Where, ϕ_u- ultimate toughness (Nm), ϕ_{fc}- first crack toughness (Nm)

The coefficient of determination (R^2) for this relationship is calculated to be an impressive 0.960, indicating an exceptionally strong and positive correlation between these two essential properties. Ultimate toughness plays a pivotal role in assessing the resistance of materials to fracture and their overall durability, particularly in structural and construction applications. Consequently, this profound insight into the relationship between first crack toughness and ultimate toughness in nRHA with Basalt fiber composites has the potential to inform the design and utilization of these advanced materials in a wide range of engineering and industrial applications, ultimately enhancing their performance and reliability. The relationships between first crack toughness (ϕ_{fc})) and ultimate toughness (ϕ_u) have been thoroughly analyzed in this study. For concrete mixtures incorporating RHA and nRHA with basalt fiber reinforcement, a compelling correlation was established through empirical equations. In the case of RHA concrete, the relationship was expressed as $\phi_u = (1.648 * \phi_{fc})) + 1.394$ with a coefficient of determination (R^2) of 0.937. Similarly, for nRHA concrete, the relationship was defined as $\phi_u = (1.947 * \phi_{fc}) + 23.70$ with an impressive R^2 value of 0.960. These equations reveal a strong positive association between first crack toughness and ultimate toughness. Such insights are pivotal for assessing the material's resistance to fracture and overall durability, offering valuable guidance for the design and application of these advanced concrete materials in engineering and industrial contexts.

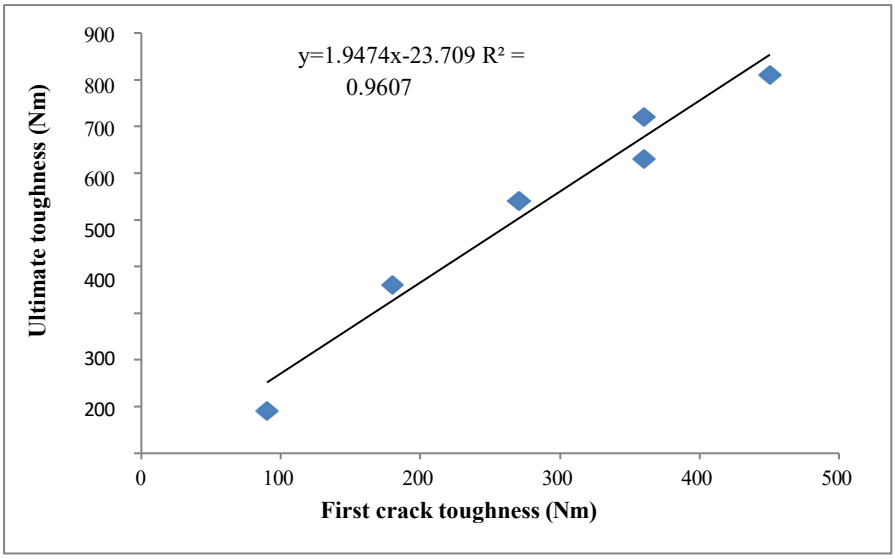


Figure 7 Relationships between first crack toughness and ultimate toughness of nRHA with basalt fiber

4.4Compressive strength (CS) of RHA and nRHA mixes

According to the CS data presented in *Table 9*, the inclusion of RHA and nRHA in BFRC mixtures generally enhanced strength up to an optimal replacement level, beyond which a decline was observed. At 28 days, the CC achieved a CS of 38.6 MPa. The strength increased progressively with the addition of RHA, reaching peak values for mixes RB2 and RB3 (containing 10% and 15% RHA, respectively) at 44.3 MPa and 43.1 MPa. However, further increases in RHA content (RB4–RB6) resulted in a reduction in strength, likely due to increased porosity and dilution of the cementitious matrix.

Table 9 Values of CS

Mix ID	RHA(kg)	nRHA(kg)	Basalt(%)	CS(Mpa)
CC	0	--	0	38.6
RB1	17.5	--	0.50	42.8
RB2	35	--	0.50	44.3
RB3	52.5	--	0.50	43.1
RB4	70	--	0.50	41.0
RB5	87.5	--	0.50	38.9
RB6	105	--	0.50	35.7
NRB1	--	17.5	0.50	45.6
NRB2	--	35	0.50	47.8
NRB3	--	52.5	0.50	48.6
NRB4	--	70	0.50	46.9
NRB5	--	87.5	0.50	44.1
NRB6	--	105	0.50	40.5

Notably, in terms of CS, the nRHA mixes (NRB series) fared better than their RHA counterparts. NRB3 (52.5 kg nRHA) had the maximum CS, measuring 48.6 MPa, which was more than 25% higher than the control. This improvement is ascribed to the nanoparticles' promotion of pozzolanic reaction, densification of the matrix, and enhancement of micro-filling. Like the RHA mixtures, excessive nRHA content beyond the optimal level led to a reduction in strength, likely due to particle agglomeration and difficulties in achieving uniform dispersion.

4.5Scanning electron microscope (SEM) analysis (at 150^{0}C & 800^{0}C) of RHA and nRHA

The SEM image of RHA at 1500°C reveals a microstructure with distinct morphological characteristics (*Figure 8*). The images clearly show that the RHA particles possess irregular, rough surfaces, typical of materials subjected to partial

combustion. The jagged edges and non-uniform particle shapes indicate incomplete burning of organic components within the rice husk. Such irregularity in morphology can significantly affect the material's packing density and, consequently, its pozzolanic reactivity when used as a supplementary cementitious material.

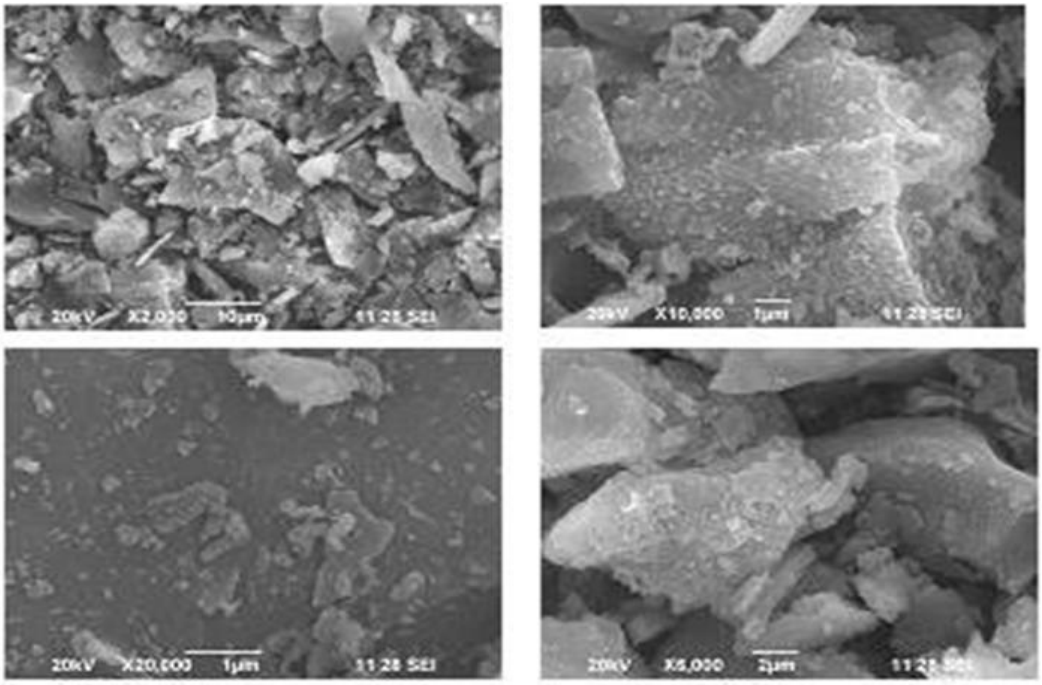


Figure 8 SEM images of 150^0C - RHA

The images display a broad distribution of particle sizes, with some particles appearing significantly larger than others. This heterogeneity is consistent with the description in the paragraph, where the larger particle sizes are attributed to incomplete combustion. The varying sizes can affect the overall reactivity and pozzolanic activity of the RHA when used in concrete, as smaller particles typically provide more surface area for chemical reactions. It reveals a porous texture on the surface of the RHA particles. These pores are crucial for the pozzolanic reactivity

of the material, as they can enhance the interaction with calcium hydroxide (Ca $(OH)_2$), a byproduct of cement hydration. The porous structure facilitates the diffusion of ions and the subsequent formation of additional cementitious compounds, leading to improved strength and durability in concrete applications. The incomplete combustion, as suggested by the presence of larger particles and the grey coloration mentioned in the text, indicates that some organic material remains in the ash. These remnants can affect the color and possibly the reactivity of the RHA, depending on the degree of carbonization and the presence of unburned organic matter.

In contrast, the SEM image of nRHA at 800^0C presents a distinctly different microstructure (*Figure 9*). Unlike the irregularly shaped and porous particles seen in RHA at lower temperatures, the nRHA particles at 800^0C exhibit a more uniform and spherical shape. This morphology is a direct result of the high-temperature calcination process, which promotes the formation of more refined and consistent particle structures.

The spherical morphology and uniformity of the nRHA particles indicate that the high-temperature treatment effectively removed the organic constituents of the rice husk. This complete combustion process at 800°C resulted in the formation of highly crystalline and pure ash particles, as evidenced by the absence of porous features. The fine, uniform, and spherical nature of the nRHA particles markedly enhances their pozzolanic reactivity. The increased specific surface area facilitates the formation of C–S–H gel, a key compound responsible for strength development and

durability in concrete. The lack of porosity further confirms the material's purity and crystallinity, both of which are critical for improving mechanical properties such as flexural toughness. The high degree of crystallinity observed in nRHA thus contributes to its superior performance in concrete applications, as demonstrated in this study.

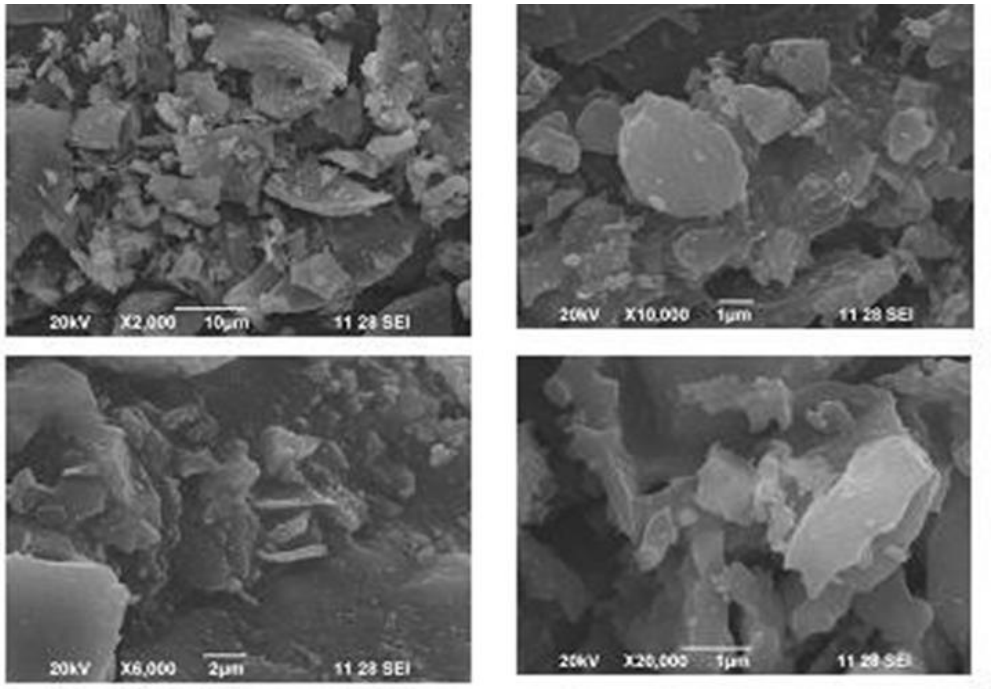


Figure 9 SEM images of nRHA calcined at 800°C

The SEM images of RHA at 150°C and nRHA at 800°C reveal pronounced differences in their microstructures, highlighting the influence of temperature on their physical and chemical characteristics. The RHA sample at 150°C displays irregular, jagged particles of varying sizes, indicative of incomplete combustion and the presence of porous structures. Such features can adversely affect packing density and reduce pozzolanic reactivity in concrete. In contrast, the nRHA sample calcined at 800°C exhibits uniform, spherical particles formed through high-temperature treatment that effectively removes organic components, producing highly crystalline and pure ash. The enhanced uniformity and absence of porosity in nRHA increase its pozzolanic reactivity, thereby improving the mechanical performance, strength, and durability of concrete.

4.6Microstructural analysis and its implications on mechanical behavior

The SEM micrographs revealed significant microstructural variations among the concrete mixes, particularly in pore distribution, matrix densification, and fiber matrix bonding. These variations were directly correlated with the observed mechanical performance. Mixes containing moderate amounts of RHA and nRHA (such as RB3 and NRB3) exhibited reduced porosity and densely packed hydration products, which contributed to higher CS and enhanced impact toughness. The nano RHA particles, owing to their extremely fine size and large specific surface area, acted as micro-fillers that efficiently filled voids and refined the pore structure. The superior toughness values observed in NRB3 (ϕ_{fc} = 20.2 J, ϕ_u = 58.1 J) demonstrate that improved particle packing not only strengthened the matrix but also enhanced energy dissipation capacity under impact loading.

In contrast, SEM images of mixes with higher RHA/nRHA contents (RB6 and NRB6) revealed agglomeration of unreacted particles and increased porosity. These defects likely weakened the fiber matrix interface and generated localized stress concentration zones. Although basalt fibers were still embedded within the matrix, such structural imperfections accounted for the reduction in both CS and impact toughness. Moreover, the optimized mixes exhibited a more continuous and well-integrated ITZ,

which enhanced crack-bridging and energy absorption during impact.

Overall, the SEM findings confirm that an optimized concentration of RHA/nRHA not only improves matrix density and interfacial bonding but also enhances the synergistic interaction with basalt fibers under dynamic loading providing strong micro-structural evidence in support of the mechanical performance trends.

It is crucial to understand that long-term durability parameters, such as water absorption, drying shrinkage, and fatigue resistance are equally important for evaluating performance in practical applications, even though the impact toughness and CS of BFRC mixes incorporating RHA and nRHA are the primary focus of this study. It is anticipated that the addition of highly reactive pozzolans, such as nRHA, will refine the pore structure and reduce permeability, thereby enhancing resistance to chemical and moisture intrusion. However, these aspects have not yet been empirically examined.

To gain deeper insight into the ageing behaviour of BFRC composites, future studies should incorporate water absorption tests, autogenous and drying shrinkage monitoring, and cyclic fatigue testing under repeated loading. The inclusion of such durability assessments would enable a more comprehensive evaluation of the material's suitability for infrastructure exposed to harsh environmental conditions or dynamic service loads.

The experimental results demonstrate that the controlled incorporation of RHA, nRHA, and basalt fibers significantly enhances the impact performance of concrete, with the effectiveness primarily governed by mix proportions and particle characteristics. The RB3 mix exhibited the highest initial and ultimate impact toughness, confirming the role of RHA in improving crack resistance under dynamic loading. Similarly, the NRB4 mix showed superior toughness values, emphasizing the benefits of combining nRHA with basalt fibers to achieve improved energy absorption.

CS results further supported these findings, with NRB3 achieving a strength of 48.6 MPa due to the superior pozzolanic reactivity and densification effects of nano-sized particles. However, excessive OPC replacement led to reduced strength, highlighting the necessity of maintaining optimal replacement levels.

SEM analysis provided further insights, revealing that sintering RHA at 150°C significantly reduced particle size while increasing silica content, thereby enhancing matrix bonding and reducing porosity. These microstructural improvements directly contributed to higher CS and impact toughness, although excessive RHA or nRHA replacement introduced micro-structural defects.

Collectively, the findings confirm that the synergy between basalt fibers and optimally proportioned RHA/nRHA plays a vital role in achieving durable and impact-resistant concrete. Nevertheless, dosage and processing parameters must be carefully controlled to prevent adverse effects on overall performance.

4.7Limitations

While the present study provides valuable insights into the bond–slip behavior and impact performance of BFRC incorporating RHA and nRHA, certain limitations must be acknowledged.

Firstly, the experimental investigation was conducted under controlled laboratory conditions, which may not fully replicate the complex environmental and loading conditions encountered in real structural applications. The impact loading tests were limited to single-drop scenarios and did not consider repeated or fatigue-type dynamic impacts that could occur in service environments. Secondly, the study primarily focused on short-term mechanical properties such as impact toughness and CS. Long-term durability parameters—such as permeability, shrinkage, fatigue resistance, and chemical attack behavior were not evaluated, though they play a critical role in determining real-world performance and service life. Thirdly, the study was restricted to a single fiber volume fraction (0.5% basalt fiber). The influence of varying fiber contents, fiber lengths, and orientations on impact resistance and bond–slip behavior remains unexplored. Furthermore, while micro-structural observations were performed using SEM, quantitative analysis techniques such as energy-dispersive X-ray spectroscopy (EDS) could provide deeper insights into phase composition and interfacial bonding mechanisms.

Finally, the empirical relationships developed between first-crack and ultimate toughness were based on a limited number of mix combinations. These correlations, though statistically strong, require further validation through extended experimental data

and numerical modeling to ensure broader applicability.

Future studies should therefore focus on the combined effects of multi-level dynamic loading, fiber dosage optimization, long-term durability evaluation, and advanced micro-structural characterization to develop a more comprehensive understanding of the behavior of BFRC with RHA and nRHA under practical service conditions. A complete list of abbreviations is listed in *Appendix I.*

5.Conclusion and future work

This study examined the combined influence of RHA, nRHA, and basalt fiber reinforcement on the impact behavior of concrete. The results highlight that RB3 exhibited the highest initial and ultimate impact toughness among RHA-based mixes, while NRB4 achieved superior crack and impact toughness among nRHA mixes. These mixtures demonstrated excellent resistance to impact forces and improved durability. The incorporation of RHA and nRHA enhanced the CS of basalt fiber-reinforced concrete (BFRC), with NRB3 achieving the maximum strength of 48.6 MPa. The superior performance of nRHA is attributed to its high pozzolanic reactivity and matrix densification, though excessive replacement levels led to reduced strength—indicating the need for optimal dosage. SEM analysis revealed that sintering RHA at 150 °C reduced particle size and increased silica content, contributing to better matrix bonding and lower porosity. Concrete without fibers exhibited brittle failure under impact, whereas basalt fiber reinforcement significantly improved energy absorption and crack resistance. Overall, RB3 and NRB4 emerged as the most promising mixtures for impact-resistant applications. The findings highlight the importance of optimizing RHA/nRHA content, controlling thermal treatment, and integrating basalt fibers to enhance the strength and toughness of cementitious composites.

Future work

Future research should focus on evaluating the long-term durability of BFRC mixtures incorporating RHA and nRHA. This includes investigating fatigue behavior under repeated loading, as well as assessing water absorption, shrinkage, and freeze–thaw resistance. Advanced characterization techniques such as durability modeling, X-ray microtomography, and BET surface area analysis can provide deeper insights into pore structure evolution and aging behavior. Additionally, exploring the synergistic effects of hybrid fibers or nano-additives in combination with optimized curing regimes may further enhance the mechanical and durability properties of concrete for structural and impact-critical applications.

Acknowledgment

The authors express their sincere gratitude to the Department of Civil Engineering, Vivekanandha College of Engineering for Women, for providing the necessary laboratory facilities to conduct this research. Special thanks are extended to the Chairman and Secretary for their constant motivation and support. The authors also wish to acknowledge the reviewers and editors for their valuable comments and constructive suggestions, which have significantly improved the quality of this manuscript.

Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

The data supporting this study were obtained from experimental investigations on concrete specimens with rice husk ash, nano rice husk ash and addition of basalt fiber. While the data are not publicly available, they may be provided by the corresponding author upon reasonable request.

Author's contribution statement

Saravanan MM: Conceptualization, Methodology, Investigation, Derivation and Numerical Analysis, Writing – Original Draft, Writing – Review and Editing. **Ananthakumar Ayyadurai:** Conceptualization, Methodology, Investigation, Derivation and Numerical Analysis, Writing – Original Draft, Writing – Review and Editing. **Dineshkumar G:** Supervision, Guidance, Review, and Technical Validation. **Sivaraja M:** Supervision, Guidance, Review, and Technical Validation.

References

[1] Di SL, Albuhairi D, Medeiros JM. Exploring innovative resilient and sustainable bio-materials for structural applications: hemp-fibre concrete. Structures. 2024; 68(2024):1-17. Elsevier.

[2] Murali G, Wong LS, Abid SR. A comprehensive review of drop weight impact testing: evaluating the pros and cons in fiber-reinforced concrete performance assessment. Journal of Building Engineering. 2024; 94:109934.

[3] Tabrizikahou A, Kuczma M, Czaderski C, Shahverdi M. From experimental testing to computational modeling: a review of shape memory alloy fiber-reinforced concrete composites. Composites Part B: Engineering. 2024; 281:111530.

[4] Ahmad I, Shokouhian M. Enhancing concrete pavement durability with recycled steel fiber extracted from waste tire. In international conference on transportation and development 2024 (pp. 293-305). ASCE.

[5] Hussein N, Abou EM, Alturki M, Elsayed M. Enhancing flexural performance of rubberized

concrete beams through incorporation of rice husk ash as cement replacement. Engineering Structures. 2025; 330:119958.
[6] Prasanna SC, Balakrishnan M, Abbas SM, Ramesh G. Characterization of basalt/bamboo Fiber reinforced sea urchin testa derived chitin-toughened epoxy composite. Journal of the Australian Ceramic Society. 2025:1-11.
[7] Khalid N. Literature review on the use of basalt fiber sheets for improving shear resistance in high-strength concrete beams. Al-Rafidain Journal of Engineering Sciences. 2025:19-41.
[8] Elhadary R, Bassuoni MT, Azzam A. Projecting the resiliency of nano-modified cementitious composites with hybrid BFP/PVA fibers in shear key joints. Structures. 2024; 63(2024):1-18.
[9] Nikmehr B, Kafle B, Al-ameri R. Long-term structural behaviour of marine-conditioned geopolymer concrete cast with geopolymer-coated recycled concrete aggregates and basalt fibres. Smart and Sustainable Built Environment. 2025 :1-36.
[10] Milling A, Amato G, Taylor S, Moreira P, Braga D. Dynamic tensile response of basalt fibre grids for textile-reinforced mortar (TRM) strengthening systems. Polymers. 2025; 17(2):1-26.
[11] Kumar P, Gogineni A, Upadhyay R. Mechanical performance of fiber-reinforced concrete incorporating rice husk ash and recycled aggregates. Journal of Building Pathology and Rehabilitation. 2024; 9(2):144.
[12] Albqour N, Shehata M, Elsayad Z, Rababeh S. Sustainable concrete-based structures: review for the potential benefits of basalt fiber reinforced concrete (BFRC) in enhancing the environmental performance of buildings. In keep on planning for the real world. climate change calls for nature-based solutions and smart technologies. 29th international conference on urban development, regional planning and information society 2024 (pp. 775-86). REAL CORP.
[13] Mohan AM, Kaliappan S, Natrayan L, Maranan R. Real-time performance analysis of nano-enhanced concrete for high-strength and crack-resistant infrastructure applications. Matéria (Rio De Janeiro). 2025; 30: e20240968.
[14] Sun L, Fu J, Wang D, Haeri H, Guo CL, Cheng H. Investigating the effect of various fibers on plasticity and compressive strength of concrete samples. Strength of Materials. 2024; 56(1):200-8.
[15] Kazemi F, Shafighfard T, Yoo DY. Data-driven modeling of mechanical properties of fiber-reinforced concrete: a critical review. Archives of Computational Methods in Engineering. 2024; 31(4):2049-78.
[16] Kychkin AK, Startsev OV, Lebedev MP, Krotov AS, Kychkin AA, Gavrilieva AA. Durability of basalt-and glass fiber-reinforced polymers: influence of internal stresses, mass loss modeling, and mechanical/thermomechanical properties under extreme cold climate exposure. Polymers. 2025; 17(18):1-19.
[17] Akbulut ZF, Tawfik TA, Smarzewski P, Guler S. Advancing hybrid fiber-reinforced concrete: performance, crack resistance mechanism, and future innovations. Buildings. 2025; 15(8):1-33.
[18] Chen C, Ding Y, Wang X, Bao L. Recent advances to engineer tough basalt fiber reinforced composites: a review. Polymer Composites. 2024; 45(14):12559-74.
[19] Muñoz-pérez SP, Sánchez-díaz E, Barboza-culqui D, García-chumacero JM. Use of recycled concrete and rice husk ash for concrete: a review. Journal of Applied Research and Technology. 2024; 22(1):138-55.
[20] Arabani M, Ebrahimi M, Shalchian MM, Majd RM. Influence of biomass-modified asphalt binder on rutting resistance. Advances in Civil Engineering. 2024; 2024(1):1-27.
[21] Kumar S, Gangotra A, Barnard M. Towards a net zero cement: strategic policies and systems thinking for a low-carbon future. Current Sustainable/Renewable Energy Reports. 2025; 12(1):1-13.
[22] Chen L, Hu Y, Wang R, Li X, Chen Z, Hua J, et al. Green building practices to integrate renewable energy in the construction sector: a review. Environmental Chemistry Letters. 2024; 22(2):751-84.
[23] Fang Z, Wang P, Zhou J, Xu H, Zheng K, Chan NW, et al. Marine photovoltaic industry development: a review of its impact on aquatic environmental elements and future perspectives. Environmental Management. 2025:1-4.
[24] Okatta CG, Ajayi FA, Olawale O. Enhancing organizational performance through diversity and inclusion initiatives: a meta-analysis. International Journal of Applied Research in Social Sciences. 2024; 6(4):734-58.
[25] Manu BA. Innovative construction materials: advancing sustainability, durability, efficiency, and cost-effectiveness in modern infrastructure. International Journal of Research Publication and Reviews. 2024; 5(12):4987-99.
[26] Shariati M, Ghaebi H, Rashidzadeh H, Khosroshahi AR. A comprehensive thermo-economic assessment of an integrated poly-generation plant powered by biomass and natural gas. Journal of Thermal Analysis and Calorimetry. 2025; 150(3):1983-98.
[27] Llanos-ruiz D, Abella-garcía V, Ausín-villaverde V. Virtual reality in higher education: a systematic review aligned with the sustainable development goals. Societies. 2025; 15(9):1-59.
[28] Atef A, Hossain Z. Assessing the impact of rice husk ash on soil strength in subgrade layers: a novel approach to sustainable ground engineering. Sustainability. 2025; 17(12):1-24.
[29] Singh N, Sharma RL, Yadav K. Sustainable solutions: exploring supplementary cementitious materials in construction. Iranian Journal of Science and Technology, Transactions of Civil Engineering. 2025; 49(3):2191-224.
[30] Kumbasaroglu H, Kumbasaroglu A. Applicability of agro-waste materials in structural systems for building

construction: a scoping review. Applied Sciences. 2024; 15(1):1-36.
[31] Abbas MM, Muntean R. The effectiveness of different additives on concrete's freeze–thaw durability: a review. Materials. 2025; 18(5):1-30.
[32] Xu K, Yang J, He H, Wei J, Zhu Y. Influences of additives on the rheological properties of cement composites: a review of material impacts. Materials. 2025; 18(8):1-34.
[33] Mahesh R, Kumar S, Pandit P. Sustainable concrete development using groundnut shell ash: a response surface methodology approach. Cleaner Waste Systems. 2025; 12:1-21.
[34] Kaboré A, Maref W, Ouellet-plamondon CM. Hygrothermal performance of the hemp concrete building envelope. Energies. 2024; 17(7):1-21.
[35] Karyappa R, Cheng JL, Ho CL, Wang S, Thitsartarn W, Kong J, et al. Unlocking the potential of liquid crystals as phase change materials for thermal energy storage. Energy Materials. 2025; 5(4):1-28.
[36] Sakkampang K, Tasenhog P, Onsalung N, Huchaiyaphum N. A study of biomass concrete reinforced with fiber composites to enhance impact load capacity. Civil Engineering Journal. 2025; 11(2):746-62.
[37] Ayyadurai A, Muthuchamy SM, Gopalakrishnan D, Govindharaju V. A comprehensive comparative analysis of the impact of metakaolin and fly ash additions on the mechanical performance of fiber-reinforced concrete beams. Matéria (Rio De Janeiro). 2025; 30:1-24.
[38] Saravanan MM, Ayyadurai A, Viswanathan G, Sasikumar P. Enhancing strength and durability of concrete: a comparative analysis of metakaolin and fly ash replacement. International Journal of Advanced Technology and Engineering Exploration. 2025; 12(122):20-37.
[39] Maruthai SM, Ayyadurai A, Muthu D, Palanisami S. Optimizing concrete performance through metakaolin and flyash incorporation: a critical appraisal of regression modeling and design code applicability. Matéria (Rio De Janeiro). 2024; 29:1-22.



Dr. Saravanan MM received the Ph.D. degree in Civil Engineering from Anna University, Chennai, Tamil Nadu, India. He is currently serving as an Associate Professor and Head of the Department of Civil Engineering, Vivekanandha College of Technology for Women, Tiruchengode, Tamil Nadu, India. His professional and research interests include concrete technology, nanotechnology, transportation engineering, composite structures, and special concretes.
Email: saromms@gmail.com



Dr. Ananthakumar Ayyadurai received Ph.D., degree in Civil Engineering (CE) from Anna University, Chennai, Tamilnadu, Currently, he is working as an Associate Professor, Department of Civil Engineering, Vivekanandha College of Engineering for Women, Tiruchengode, Tamilnadu, India. His professional and research interests include concrete technology, transportation, composite structures and special concretes.
Email: ananthaakumar7410@gmail.com



Dr. Dineshkumar G received Ph.D., degree in Civil Engineering (CE) from Anna University, Chennai, Tamilnadu, Currently, he is working as an Associate Professor, Department of Civil Engineering, Vaagdevi College of Engineering, Telengana, India. His professional and research interests include concrete technology, composite structures and special concretes.
Email: gdkcivil@gmail.com



Dr. Sivaraja M, a goal-driven professional born in 1974, emerged as a Gold Medalist in his Postgraduate and Ph.D. studies at Anna University and completed his Postdoctoral research at SUNY Buffalo, USA, under the BOYSCAST Fellowship. His dedication and commitment led him to become the Founder Principal of N.S.N. College of Engineering and Technology, Karur, in 2011, at the age of 37. He is currently serving as a Professor and Principal at Nehru Institute of Technology, Coimbatore.
Email: m.shivaraja2006@gamil.com

Appendix I

S. No.	Abbreviation	Description
1	ACI	American Concrete Institute
2	ASTM	American Society for Testing and Materials
3	BET	Brunauer–Emmett–Teller
4	BFRC	Basalt Fiber Reinforced Concrete
5	CC	Conventional Concrete
6	CS	Compressive Strength
7	C-S-H	Calcium Silicate Hydrate
8	ECC	Engineered Cementitious Composites
9	EDS	Energy-Dispersive X-ray Spectroscopy
10	FRC	Fiber-Reinforced Concrete
11	ITZ	Interfacial Transition Zone
12	NRB	Nano Reinforced Beam
13	nRHA	Nano Rice Husk Ash
14	OPC	Ordinary Portland Cement
15	RB	Reinforced Beam
16	RHA	Rice Husk Ash
17	XRD	X-Ray Diffraction