



Synergistic Effects of Rice Husk Ash and Alccofine in Basalt Fiber Reinforced Concrete: A Comprehensive Review of Mechanical, Durability and Microstructural Performance

Sahil Samanta ^{a,*}, N. Lingeshwaran ^a

^a Department of Civil Engineering, Koneru Lakshmaiah Education Foundation (Deemed to be University), Guntur, Vaddeswaram, India

* Corresponding Author Email: sanjusahil777@gmail.com

DOI: <https://doi.org/10.54392/irjmt2623>

Received: 28-11-2025; Revised: 24-01-2026; Accepted: 14-02-2026; Published: 09-03-2026



Abstract: The increased need in sustainable and high strength concrete has aggravated the interest in the application of basalt fibers along with the additional cementitious materials (SCM). However, there is experiment research that has directly examined the combined effect of rice husk ash (RHA) and Alccofine in basalt fiber-reinforced concrete (BFRC). This review is a critical review of published literature on mechanical performance, durability, and micro-structure of BFRC and other cementitious systems that use these SCMs. RHA is a reactive, amorphous silica enhanced to increase the long-term pozzolanic potential, and Alccofine is a calcium-rich ultrafine slag, which increases early age hydration and densifies the matrix. In independent research, such materials combined generally increase the strength by 15–25% and decrease significantly permeability, chloride intrusion and sulfate-based corrosion. These enhancements are deduced by individual studies of RHA modified, Alccofine modified and fiber reinforced concretes, due to absence of direct comparative data to the ternary RHA–Alccofine–BFRC. SEM and XRD micro-structural evidence continue to provide evidence of pore refinement, increased formation of C–S–H gel, and increased fiber-matrix bonding in the face of mechanical, chemical and thermal exposure. Even with these promising results, there are still gaps in conventional SCM processing, field validation over long-term and quantitative connections between micro-structure and performance. In general, this review summarizes the available literature to explain the theoretical and mechanistic capability of RHA and Alccofine synergy in BFRC, and emphasize the importance of systematic experimental verification to verify its feasibility as a long-lasting, low-carbon, high-performance material in current building.

Keywords: Basalt Fiber Reinforced Concrete, Rice Husk Ash, Alccofine, Supplementary Cementitious Materials, Microstructure

1. Introduction

Concrete is the most popular building material in the world as it is compressively strong, may be modified to numerous purposes, and is economical [1, 2]. Nonetheless, this popularity is at a high environmental price. The primary binder is ordinary Portland cement (OPC), and the manufacturing of this material produces nearly 8% of the annual CO₂ burden around the planet [3]. Traditional OPC concrete has other mechanical and durability disadvantages: low tensile strength, brittle cracking, and progressive degradation under chlorides, chemical and freeze thaw conditions, as demonstrated in recent durability research [4–6]. All these problems have increased the study on sustainable concrete that incorporates additional cementitious materials (SCMs) with fiber reinforcement to improve the strength and durability [7–9]. Figure 1 presents the conceptual map to

be used in this research on sustainable concrete. The diagram itself is connected to the environmental constraints of the conventional concrete, targeting the interventions, which are the addition of SCMs and basalt fibers. The primary effect of SCMs is the reduction of waste and the increase of C–S–H formation that makes the matrix denser and decreases porosity. Basalt fibers, in their turn, enhance crack-bridging and retardation of crack propagation. The main synthesis route in the diagram focuses on the synergistic effect of SCMs and basalt fibers, which is the experimental basis of the mechanical and sustainability results obtained here.

Fiber reinforced concrete (FRC) has been researched extensively as a method of enhancing ductility, crack resistance and energy absorption of cementitious composites [10, 11].

Sustainable Concrete Development Process

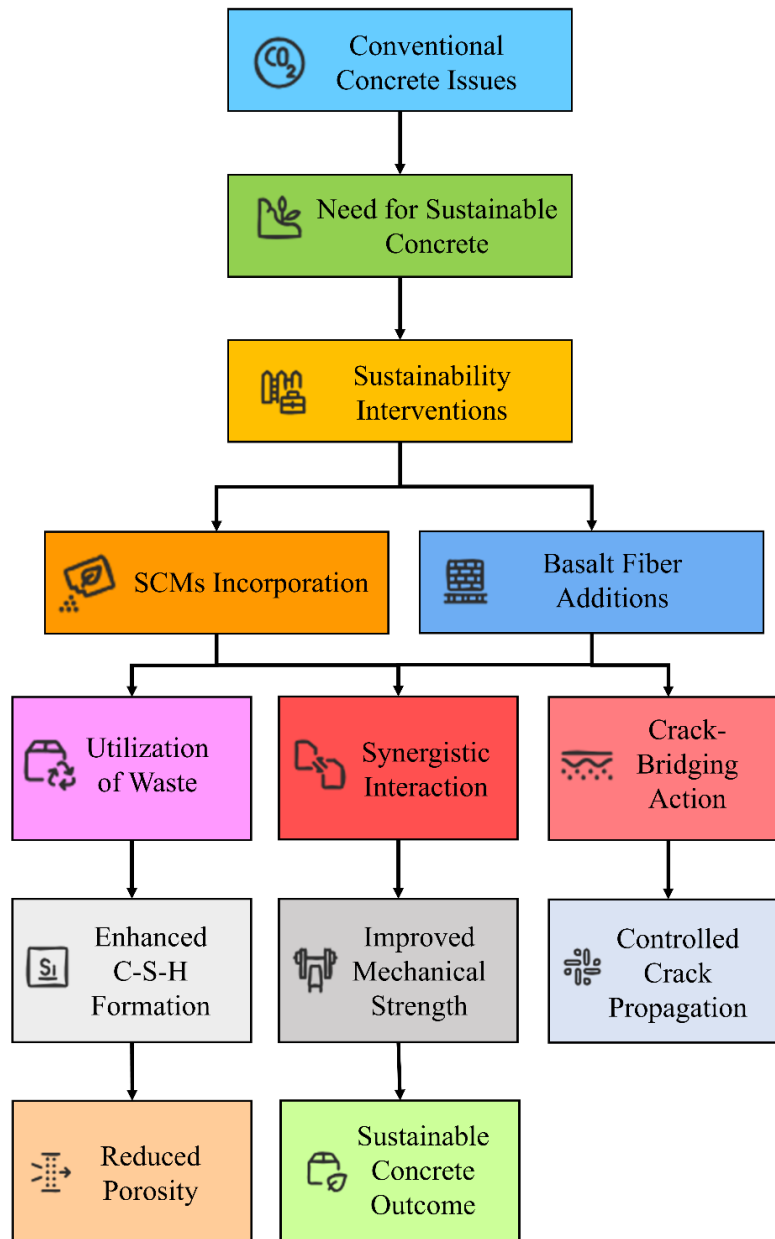


Figure 1. Sustainable concrete development conceptual framework, which shows how supplementary cementitious materials (SCMs) and basalt fibers interact to refine the pores, regulate cracks, and improve the overall mechanical performance.

Of the most frequently employed fibers, including steel, polypropylene, glass, and carbon, basalt fiber (BF) has been receiving more and more attention. BF provides a compromise between mechanical performance, durability, and environmental friendliness [12, 13]. It is made with natural volcanic rock, tensile strength of 2.5–4.8 GPa, great chemical stability, and corrosiveness and production does not add toxic additives or emissions [14, 15]. The contribution of short BF, when evenly distributed across the cement matrix, is that it creates a network of crack-bridging and increases

stress transfer, crack growth, and interfacial transition zone (ITZ), leading to the improvement of post-cracking behaviour [16, 12]. It has always been tested that BF content of approximately 0.15–0.4% by volume enhances flexural and tensile strength and obtains slight improvements in compressive strength (usually up to 10–25% based on the mix). It also significantly decreases shrinkage-induced cracking as well as enhances post-cracking toughness as recent studies indicate [17, 18].

Table 1. Overview of the major functions and processes of basalt fibers and additive cementitious materials (SCMs) in concrete

Component	Primary Function	Mechanism	Key Benefits	References
Basalt Fibers	Crack control, ductility	Crack bridging, stress redistribution	Increase in tensile strength and decrease in shrinkage	[12-18]
Rice Husk Ash (RHA)	Pozzolanic reaction	$\text{SiO}_2 + \text{Ca(OH)}_2 \rightarrow \text{C-S-H}$	Long-term strength and lower permeability	[24, 25]
Alccofine	Ultrafine hydraulic filler	Accelerates hydration, densifies matrix	Early strength gain and packing density	[9, 20]
Combined (RHA + Alccofine)	Complementary reactivity	Silica-rich + Calcium-rich reaction	Balanced early & late strength and refined ITZ	[9, 20, 24, 25]

Along with fiber reinforcement, the supplementary cementitious materials (SCMs) application is an important approach to reduce the consumption of clinker and optimize concrete microstructure [19–21]. Other C–S–H contributing SCMs include fly ash, silica fume, ground granulated blast furnace slag (GGBS), metakaolin, rice husk ash (RHA) and Alccofine, which is also pozzolanic or latent hydraulic reactions that narrow pores and reduce permeability [21–23]. RHA is particularly appealing among them due to its high content of amorphous silica and high sustainability ratings [24, 25]. In addition to cement systems, recent studies indicate that RHA can be a hybrid biodiesel production catalyst [26] and a grain-based carbon source of energy storage [27]. These results highlight the chemical reactivity, resource efficiency, and environmental value of RHA, which makes it suitable in the use of a low-carbon SCM in concrete [21, 22, 25, 24].

Of special importance is the interaction of basalt fibers and SCMs. Fibers manage macro and meso scale cracking, and the SCMs condense the matrix and the ITZ on the micro scale and thus enhance long term durability [28, 29]. Table 1 contains the key functions and mechanisms of basalt fibers, RHA, and Alccofine and indicates how each one of them plays a role in cementitious composites, individually and jointly, in terms of strength, microstructural refinement, and crack mitigation.

A considerable number of researches have been conducted on basalt fiber reinforced concrete (BFRC) using single SCM systems, including BF with fly ash [30] or BF with silica fume [31]. But there is no direct experiment that investigated OPC based BFRC using a ternary mix of RHA and Alccofine. Therefore, the information regarding dual-SCM synergy is primarily obtained based on similar OPC systems with no fibers or non-OPC matrices. The RHA–Alccofine pair appears to be a good option, mechanistically, RHA is abundant in the amorphous silica, which facilitates long-term densification and prolonged pozzolanic reactions [32], whereas Alccofine is a calcium-rich ultrafine slag,

accelerating the early hydration and improving packing between particles [33]. These two SCMs are expected to provide complementary early and late-age benefits, which may be suitable with basalt fiber reinforcement. However, the literature typically separates SCM effects versus fiber effects, ignoring interplay of fibers, hydration products and ITZ in a multi-scale manner when the conditions remain constant. Similarly, there are no comparative syntheses that couple mechanical, durability, and microstructural performance in one framework in OPC-based BFRC with RHA and Alccofine. This gap in knowledge creates the motivation behind the current review.

Therefore, the current review summarizes and critically analyzes the existing literature on basalt fiber reinforced concrete which incorporates RHA and Alccofine and puts the work into a wider context of SCM-fiber synergy. It gives a summary of the reported trends in mechanical, durability, and microstructural performance, examines the chemical complementarity and interaction mechanisms of RHA and Alccofine, and identifies the current limitations and future research requirements of high-performance, sustainable hybrid concrete systems.

It is necessary to mention that, as of December 2025, there is no systematic experimental research done on the ternary mixture of rice husk ash, Alccofine, and basalt fibers in OPC concrete. Thus, the ternary mix performance data are not validated in this review. Rather, it uses a synthesis based on mechanisms that combines evidence of BFRC systems, binary SCM concretes, etc. to draw inferences about probable interactions, performance trends, and limits of research. The primary value of this work is that it has defined mechanistic complementarities, the limits of extrapolation, and also critical gaps that need to be filled in future experimental studies.

2. Methodology and Selection Criteria

First, the database searches were used to find approximately 400 publications. Duplicates were

eliminated, and titles and abstracts examined after which those studies that did not fit into the category of unrelated studies were excluded. After which, we examined the entire papers and eliminated articles in which no clear mix designs, testing protocols or reproducible results were reported. Recent experimentally validated studies which involved durability or microstructural analysis were accorded a greater weight in the synthesis. There was no experimental study on the ternary mixture of RHA, Alccofine, and basalt fibers in the OPC based concrete by December 2025. The review, therefore, makes conclusions based on mechanistic understanding of single and dual-SCM BFRC studies, which leads to the conclusion of 106 papers that will be discussed in more detail.

3. Basalt Fiber Reinforced Concrete: Background Role

Basalt fiber is finding application in cementitious composites due to its tensile strength, elastic modulus, thermal stability and good chemical compatibility with cementitious environment [12, 13]. Basalt fibers are formed through the extrusion and melting of natural

volcanic basalt rock and have a constant oxide composition and are resistant to attack by alkali, which are why they find application in long-term concrete applications [16, 34–36]. To be more precise, Table 2 displays the main physical, mechanical, and chemical characteristics of the basalt fibers that are typically employed in concrete.

3.1 Mechanical Performance and Fiber Effects

The key advantage of basalt fiber is that it has the capacity to distribute the stress along microcracks, which significantly enhances the performance after cracking. Compressive strength is increased by 8–20% with the best dosages of 0.075–0.6% by volume based on matrix composition and age of curing [37, 38]. The flexural and split tensile strengths also become stronger and usually increased by 20–35% due to the effect of crack-arresting basalt fibers. But above 0.5%, the content of fiber decreases the workability and the fibers may clump, restricting strength increases [39, 40]. Thus, it is critical to obtain an ideal dose of fiber and even distribution of dispersed fiber to attain mechanical performance. Figure 2 shows the relationship between compressive strength and the various fiber volumes of chopped basalt fiber-reinforced concrete (CBFRC).

Table 2. Physical, mechanical and Chemical properties of basalt fiber used in concrete [12, 13, 16], [34–36],

Property	Typical value
Density (g/cm ³)	2.60–2.80
Tensile strength (MPa)	3000–4800
Elastic modulus (GPa)	85–95
Elongation at break (%)	2.6–6
Filament diameter (μm)	10–21
Typical fiber length (mm)	6, 12, 18, 24
Melting point (°C)	1450
SiO ₂ (%)	45–56
Al ₂ O ₃ (%)	14–19
CaO (%)	8–16
MgO (%)	1–6
Fe ₂ O ₃ (%)	4–14
Alkali oxides (Na ₂ O + K ₂ O) (%)	< 7
TiO ₂	1.23
MnO	0.28
H ₂ O	0.46
P ₂ O ₅	0.26

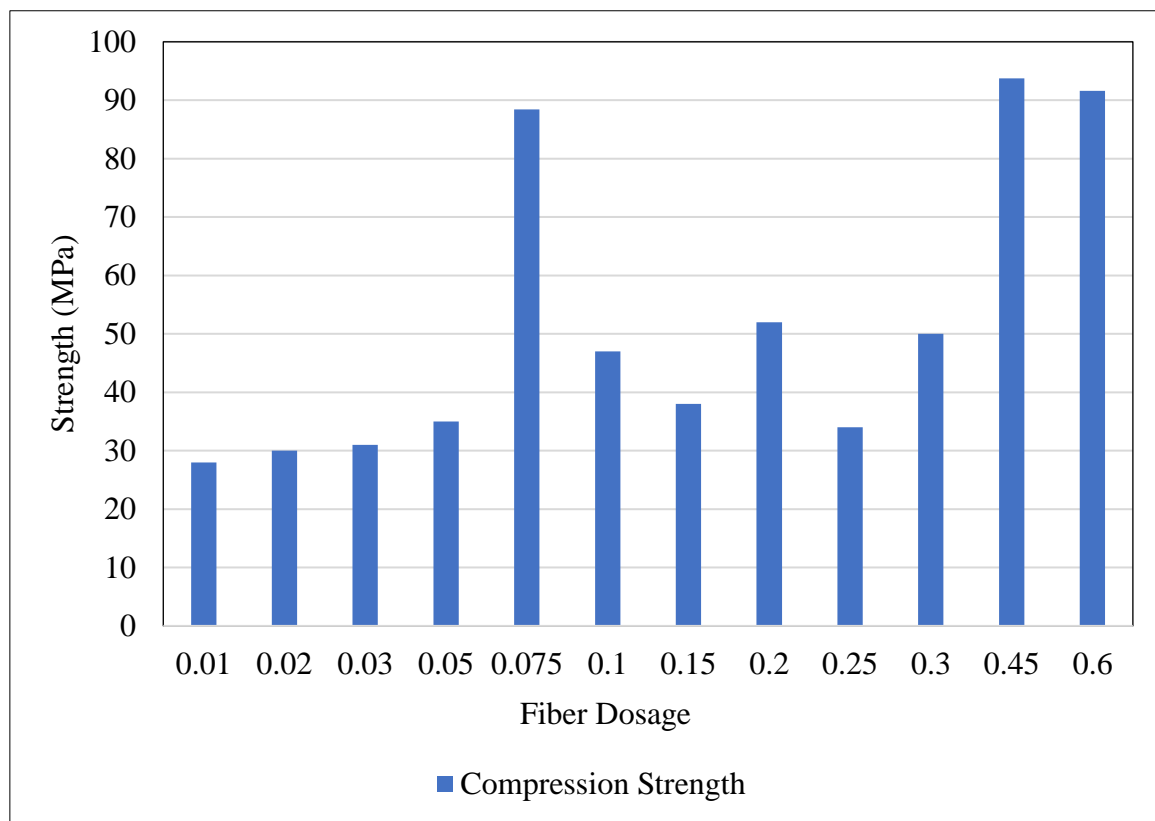


Figure 2. A plot of compressive strengths of chopped basalt fiber-reinforced concrete (CBFRC) versus different fiber volume fractions [36, 38–42].

3.1.1 Influence of Fiber Length

The length of the fiber is an important factor in workability, bridging cracks, and transfer of loads [37, 43]. Small cracks are mainly controlled by short fibers (6 mm), which increase compressive strength and reduce shrinkage [44]. The medium fibers (12 mm) are a good balance between strength, ductility, and workability providing the most favorable compressive, tensile, and flexural performance [45]. Long fibers (24 mm) increase the energy absorption and toughness but reduce workability and can form lumps, which can require the addition of additional superplasticizer [45, 46]. Figure 3 takes a summary of the fiber lengths that would provide the optimal mechanical performance.

3.1.2 Workability Considerations

The longer the fiber length or content, the lower the workability. Slump is high, and the fiber content is low (0.2%) to ensure that the flow is low, but longer fibers (6–30 mm) decrease it since they can tangle early. The effect is aggravated at medium (1%) and high (2%) fiber contents. There are hybrid mixes of 12 mm and 30 mm fibers with better slump, which exhibit enhanced flowability [46, 47]. The relationship between slump and fiber length and volume is shown as in figure 4.

3.1.3 Mechanical Performance Summary

High compression and flexural strengths are made due to the high aspect ratio of the fibers and their high bonding with the matrix [14]. Table 3 is a summary of the effect of different fiber volume in mechanical performance [15, 17, 48, 49]. Figure 5 schematically indicates that basalt fibers retard the growth of a microcrack, by bridging the growing cracks, which reallocates the stress and increases post-cracking ductility, increasing flexural and split tensile strengths.

3.1.4 Load–Deflection Behavior

Basalt fibers alter the load-deflection characteristics of brittle to ductile. They seal cracks and absorb energy thus delaying post-peak failure. Load-deflection curves show that BFRC does not lose a significant portion of its strength following cracking, and will maintain a slower load curve than plain concrete [17, 38, 41]. PVA and BF hybrid systems are characterized by good control of cracks and strain capacity [50]. The common load-deflection curves are shown in Figure 6.

3.1.5 Impact and Fatigue Resistance

The basalt fibers increase impact and fatigue resistance through an increase in energy absorption and reduction in crack propagation [18, 51].

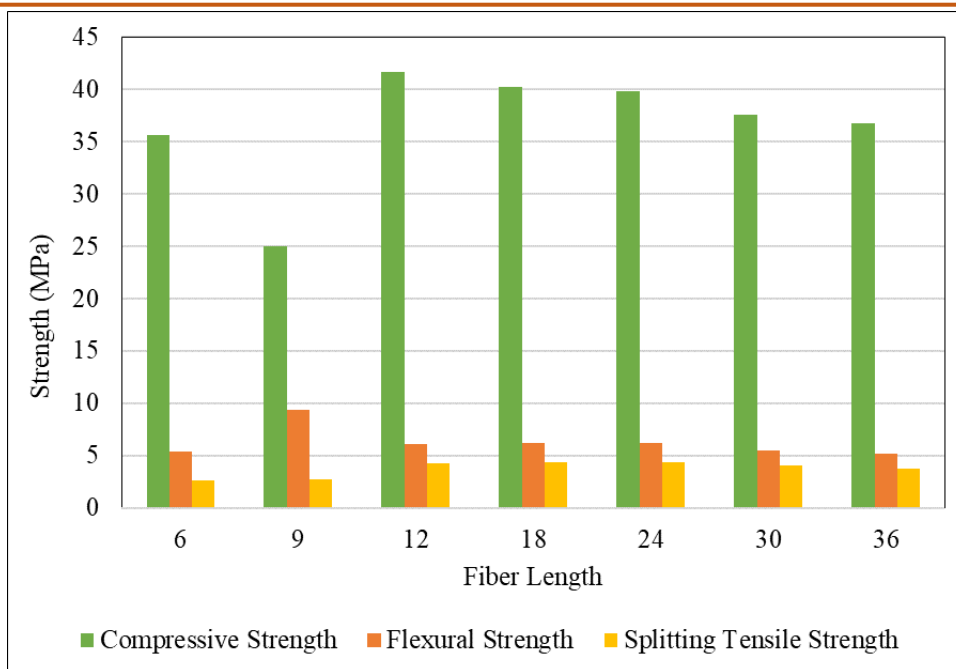


Figure 3. Basalt fiber length effect on compressive, flexural and split tensile strengths of fiber-reinforced concrete [42, 46]

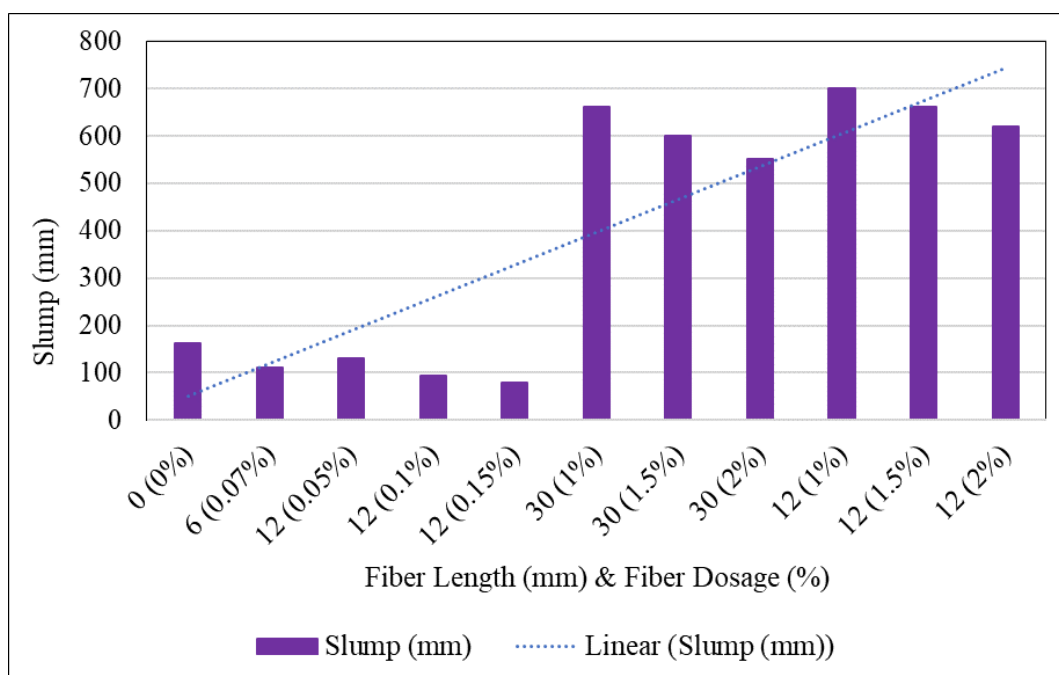


Figure 4. Slump for different chopped basalt fiber lengths and contents [46, 47].

Table 3. Synthesis of Mechanical Performance in BFRc.

Fiber Volume (%)	Change in Compressive Strength	Change in Flexural Strength	Optimum Range	Key Finding	Reference
0.1	Increase up to 6–10%	Increase up to 12–18%	Low	Improved crack control with no workability loss	[17]
0.25	Increase up to 10–20%	Increase up to 25–35%	Optimum	Balance between strength and ductility	[48]
0.5	Increase or decrease up to 0–5%	Increase or decrease up to 5–10%	High	Fiber balling, reduced flow	[15, 49]

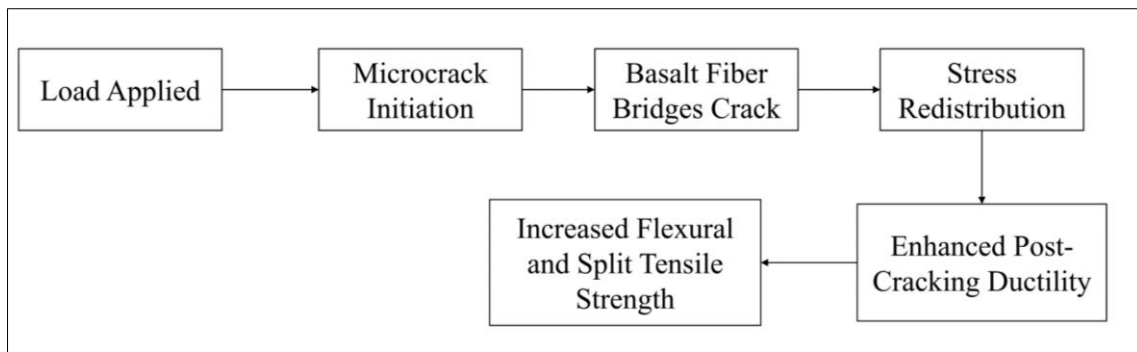


Figure 5. Diagram of the crack-bridging mechanism of basalt fibers when loaded and its influence on post-cracking ductility and tensile strengths

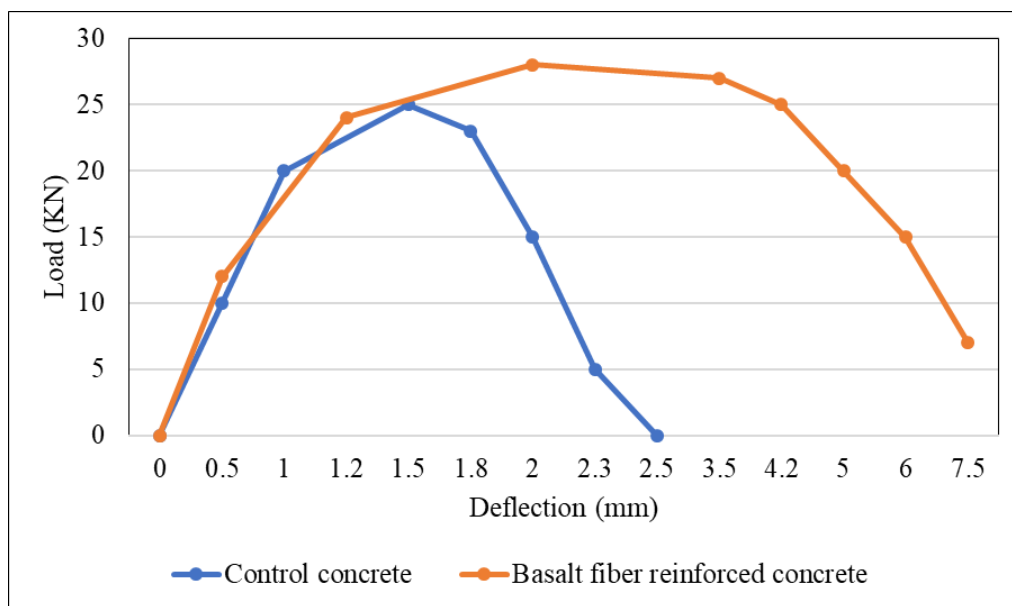


Figure 6. Load-deflection curves of BFRC and control concrete [38].

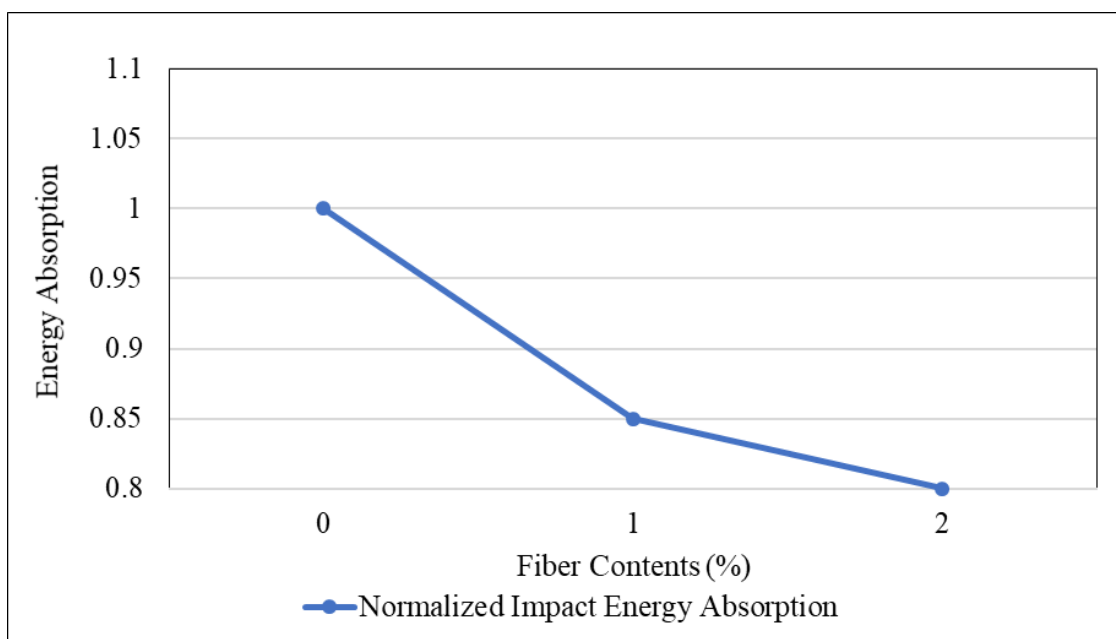


Figure 7. Impact energy absorption trend of chopped basalt fiber-reinforced concrete (CBFRC) with different fiber contents [18].

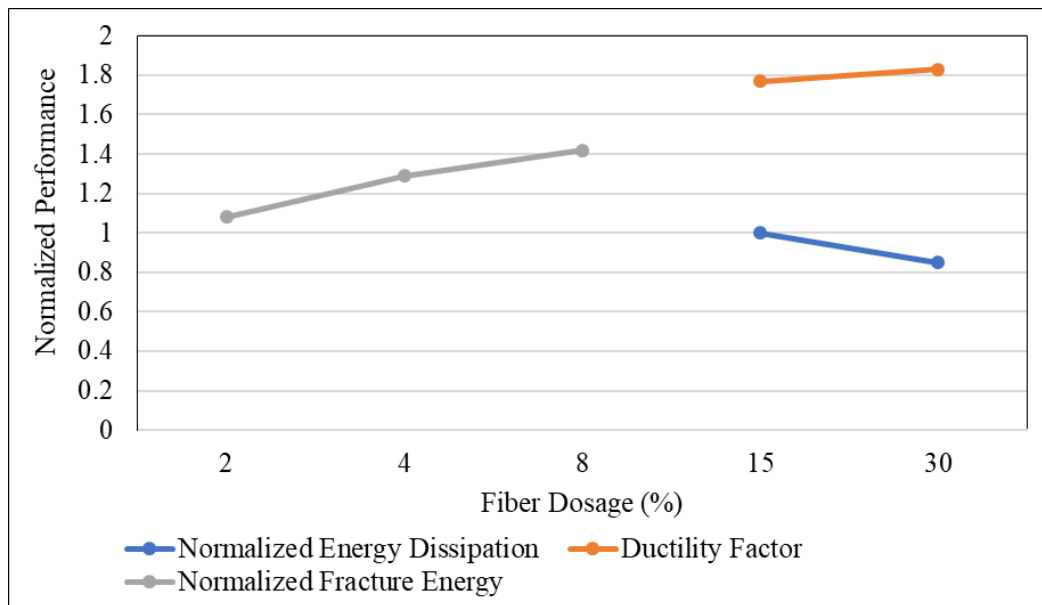


Figure 8. Effect of basalt fiber volume fraction on normalized impact energy and fatigue life [18, 51].

Table 4. Summary of reported effects of basalt fiber volume fraction and fiber length on the mechanical performance of concrete

Fiber Volume (%)	Fiber Length (mm)	Compressive Strength Change	Flexural / Tensile Strength Change	Key Observation / Mechanism	Reference
0.075–0.1	6–12	+6–10% increase	+12–18%	Low dosage improves crack control without affecting workability	[17]
0.25	12	+10–20% increase	+25–35%	Optimum balance between strength, ductility, and workability	[48]
0.5	12–24	0–5% increase/decrease	5–10% increase/decrease	High fiber content may cause clumping and reduced flow	[15, 49]
0.075–0.31	12–24	2.5% increase	Increased fracture energy / ductility	Enhances fatigue and impact resistance; fibers bridge cracks and distribute stress	[18]
1–2	12–24	1% increase	Significant ductility improvement	High fiber improves energy absorption and stability under repeated loading	[51]

Optimal results will normally be attained at a fiber content of less than 1%; any higher volumes might reduce energy absorption due to fiber clustering. Trends in impact energy absorption and normalized fatigue performance are represented in figures 7 and 8. Table 4 summarizes the reported results, showing that low to moderate fiber contents, about 0.075–0.25%. Give the most optimum combination of enhancing strength and workability, in terms of bridging cracks and redistributing stress. Conversely, when the fiber volumes are elevated, the ductility is enhanced primarily, with little or no strength enhancements.

3.2 Durability Performance

3.2.1 Permeability, Water Absorption, Chloride, and Sulfate Resistance

BFRC also demonstrates better resistance to adverse conditions, whereby, in comparison to other designs, it minimizes microcracks and optimizes pore structure [43, 52–55]. The compressive strength is still better in combined chloride-sulfate attack with the best fiber dosage of about 0.5% [53]. Low fiber contents (0.3%) have decreased water absorption and this is attributed to smaller pores and fewer connections [56,

57]. The rubberized and hybrid fiber concretes are less permeable owing to crack bridging [58]. The figures 9–11 represent the strength maintenance during the chemical assault, the patterns of water absorption, and the enhancement of compressive strength.

3.2.2 Acid, Alkali, Freeze-Thaw, and Thermal Resistance

BFRC has a high stability to acid and alkali conditions because basalt fibers are chemical stable [12,

35, 59]. Relative to the glass fiber and plain concrete, compressive strength and surface quality exhibit better performance in a chemical attack and performance of control and CBFRC specimens with alkali environment depicted in Figures 12 and 13.

Pure and hybrid BFRC systems have an increased freeze-thaw and heat resistance. The best frost resistance is at 0.15% fiber content, and the compressive strength is 30.9% greater when it is subjected to seawater freeze-thaw conditions [60, 61].

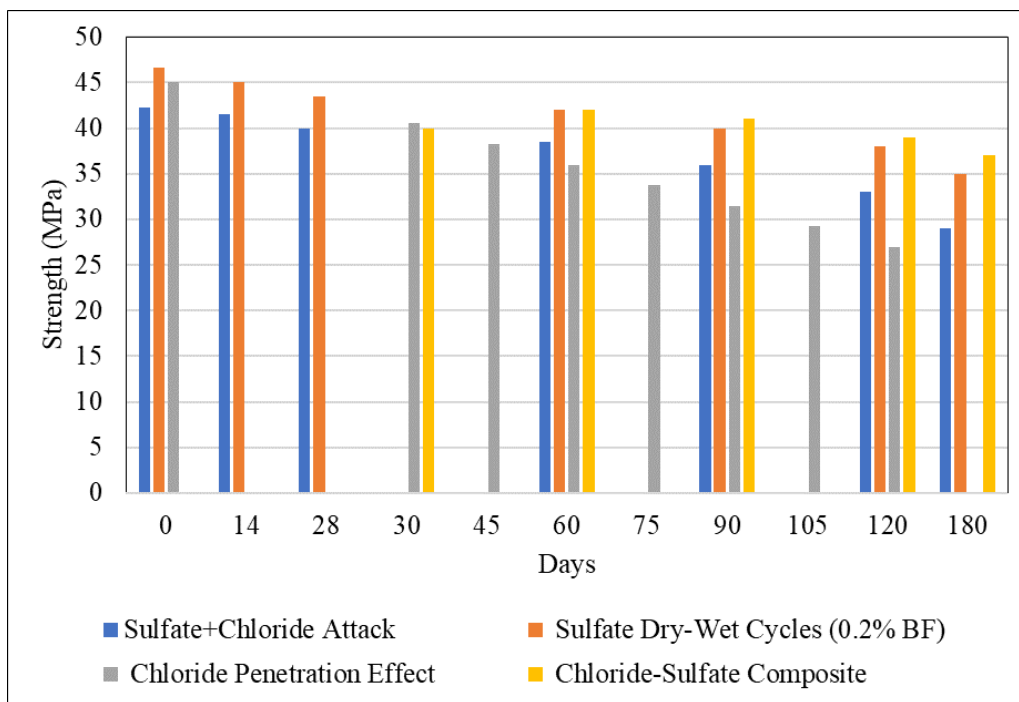


Figure 9. Compressive strength of BFRC under sulfate and chloride attack conditions over time [28, 52, 55]

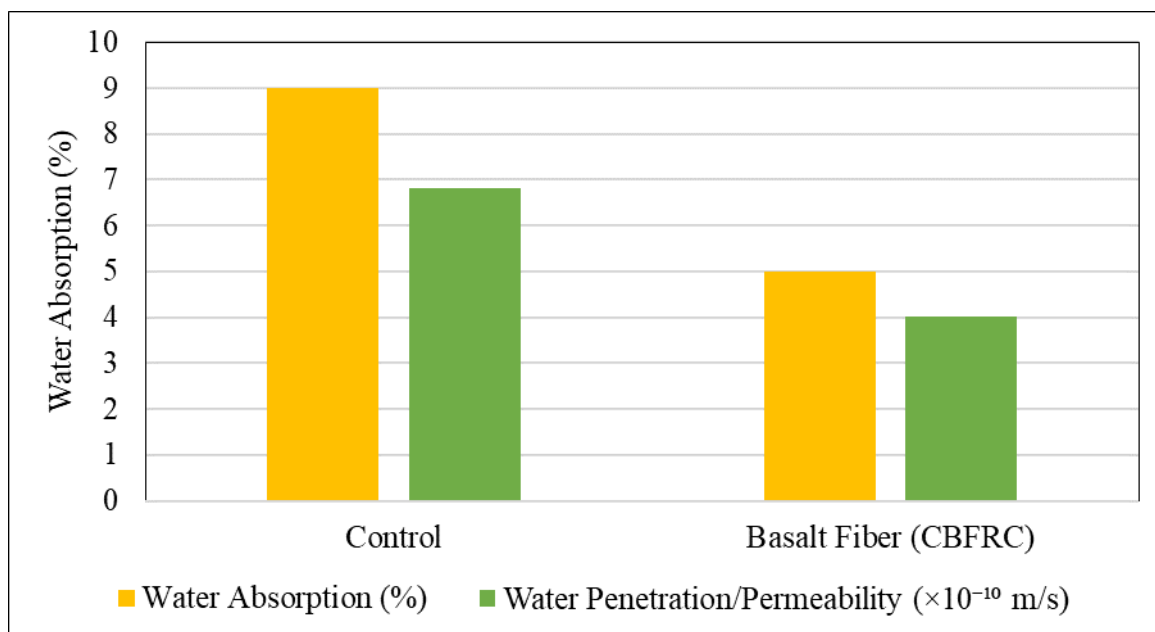


Figure 10. Comparison of water absorption (%) for control and basalt fiber concrete [56, 57].

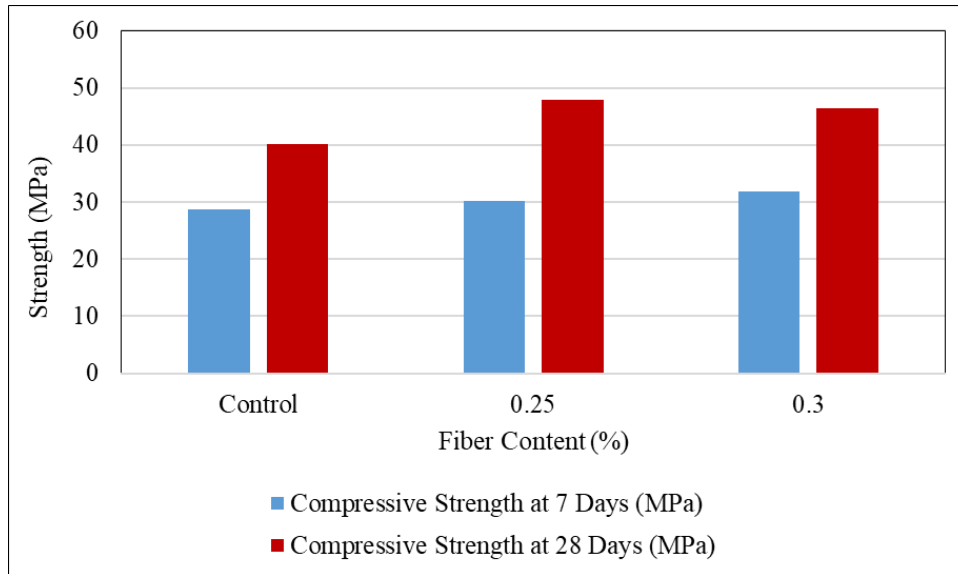


Figure 11. Improvement in compressive strength with basalt fiber incorporation compared to control [56, 57].

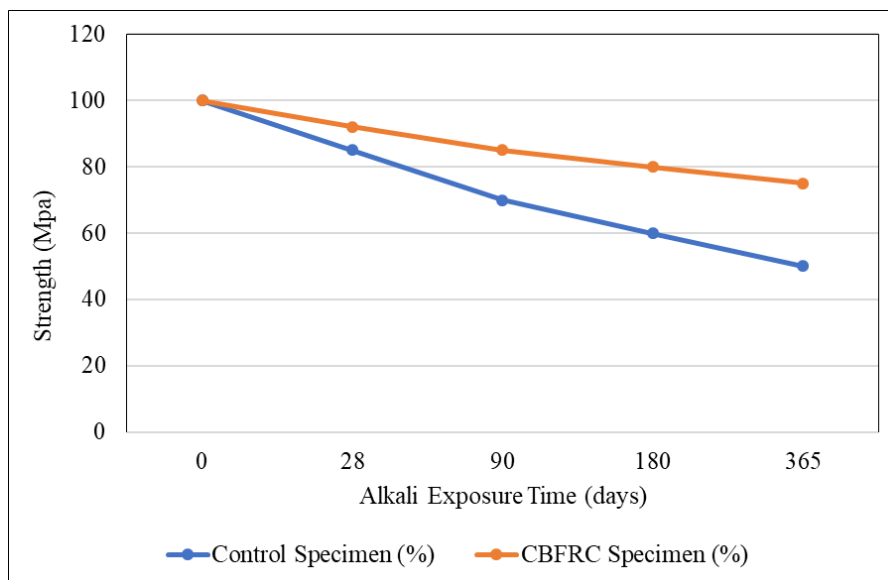


Figure 12. Expansion behavior of control and CBFRC specimens under alkali exposure [12, 35, 59].

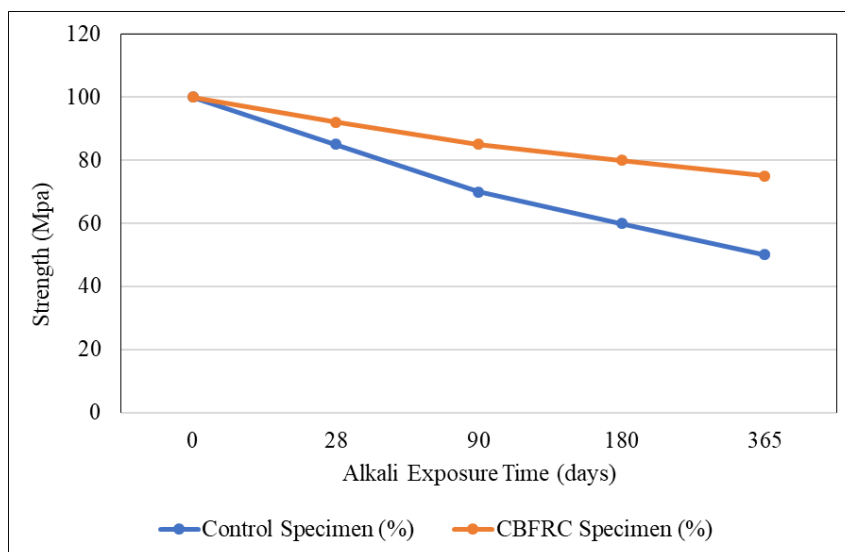


Figure 13. Residual compressive strength of control and CBFRC specimens after alkali exposure [12, 35, 59].

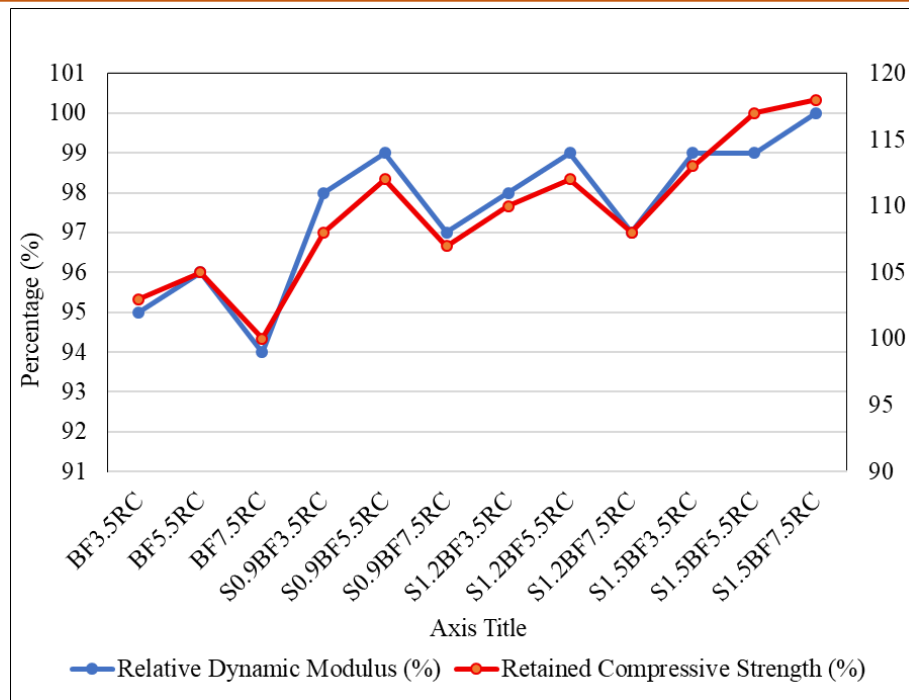


Figure 14. Relative dynamic modulus and retained compressive strength of control and basalt fiber–reinforced concrete (BFRC) mixes after 300 freeze–thaw cycles [61, 62].

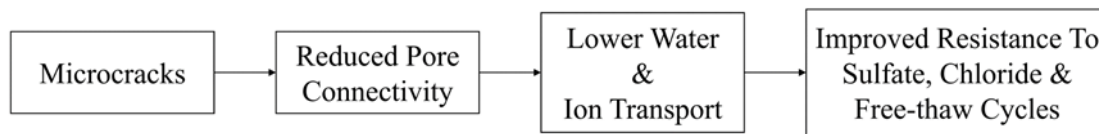


Figure 15. Schematic illustration of the durability improvement process connecting the control of microcracks with the lowering of the pore connectivity and the better resistance to the aggressive environmental activities.

Table 5. Summary of Durability Enhancements in BFRC

Exposure Type	Improvement in BFRC	Mechanism	Optimum Fiber Dosage	References
Combined chloride–sulfate attack	Strength is retained by 20–25%	Fibers reduce ettringite and gypsum growth and stabilize C–S–H and Friedel’s salt	Up to 0.5% BF	[53]
Sulfate dry–wet cycles	Strength is retained by 30%	Fibers bridge microcracks and resist expansion caused by ettringite	0.2% BF	[55]
Sulfate resistance	Strength is retained by 15–20%	Fibers protect the matrix and make the interface between fiber and cement denser	0.25%	[62]
Freeze–thaw durability	Compressive strength is 30.9% higher than plain concrete	Fibers connect microcracks and stop them from spreading	0.15%	[61]

Under sulfate-freeze-thaw cycles, hybrid fiber systems improve in strength by up to 47.5% [62]. The retention of mechanical properties at high temperatures is confirmed to be up to 650–800 °C [63–65]. In Figures

14, freeze thaw behavior of basalt fiber reinforced concrete is displayed. The minimization of microcracks as shown in Figure 15 restrains the connectivity of the pores and thus reduces the movement of water and other ions, leading to better sulfate attack, chloride ingress, and freeze-thaw resistance. An in-depth summary of the enhancement in durability in BFRC is presented in Table 5.

3.3 Microstructural Behavior

Mechanical, impact, and fatigue improvements are based on microstructural changes. Basalt fibers decrease the pore connectivity, stabilize the ITZ, and manage the crack propagation [18, 51, 66, 67]. Hybrid basalt-steel UHPC also has a better continuity of the

matrix and fatigue resistance [68]. SEM research indicates that fibers penetrate pores, seal empty spaces and increase bonding of the ITZ particularly in lightweight concrete [43]. Figure 16 shows the distribution of fibers, densification of ITZ, and compression bridging of cracks. The tests of acid and alkaline exposures show the stabilization of hydration products and micro-defects [67]. SEM, EDS, XRD and TGA analyses evidences of improved microstructure, decreased portlandite, greater amorphous C-S-H, diminished CH breakdown and thermal stability at up to 1100 °C [29, 69–73]. Figures 17–19 present the SEM/EDS outcomes in different circumstances. Table 6 summarizes the important microstructural observations and processes of BFRC.

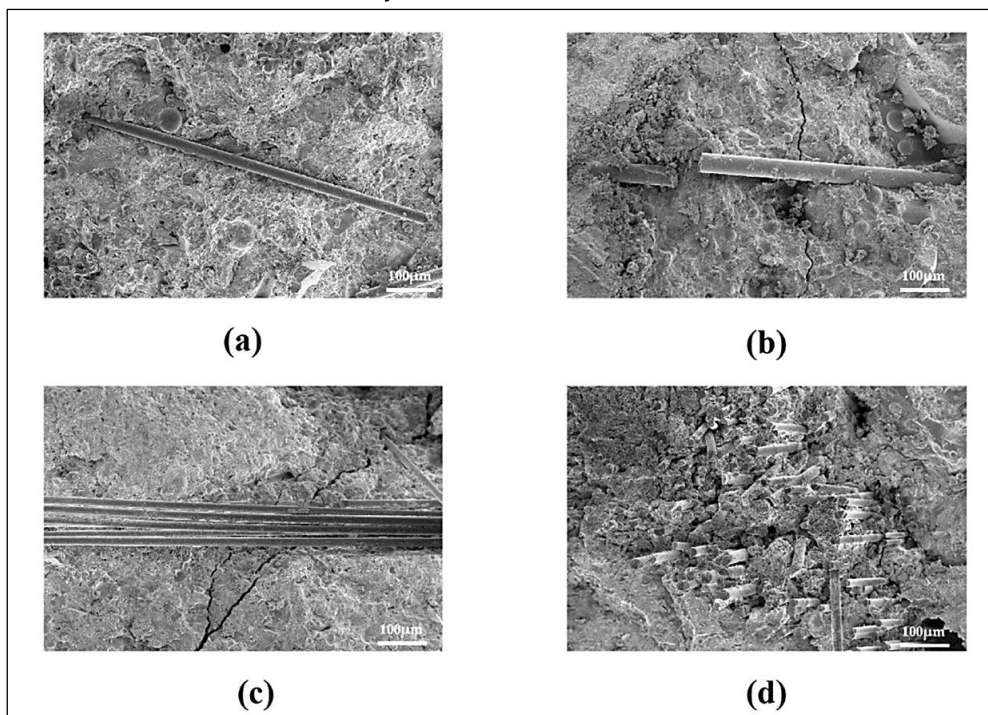


Figure 16. SEM images of BF failure [43].

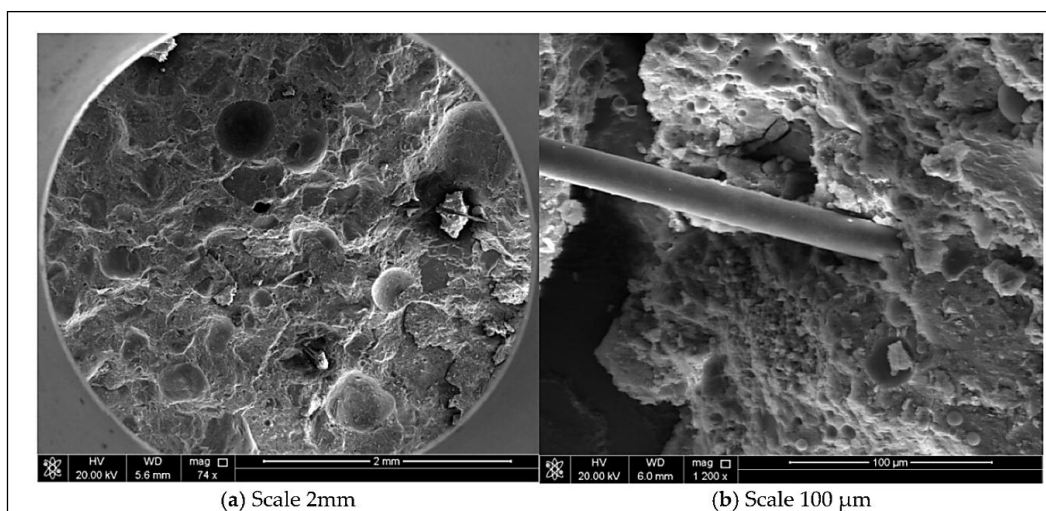


Figure 17. SEM images shows densely hydrated cement matrix near the fiber surface [30].

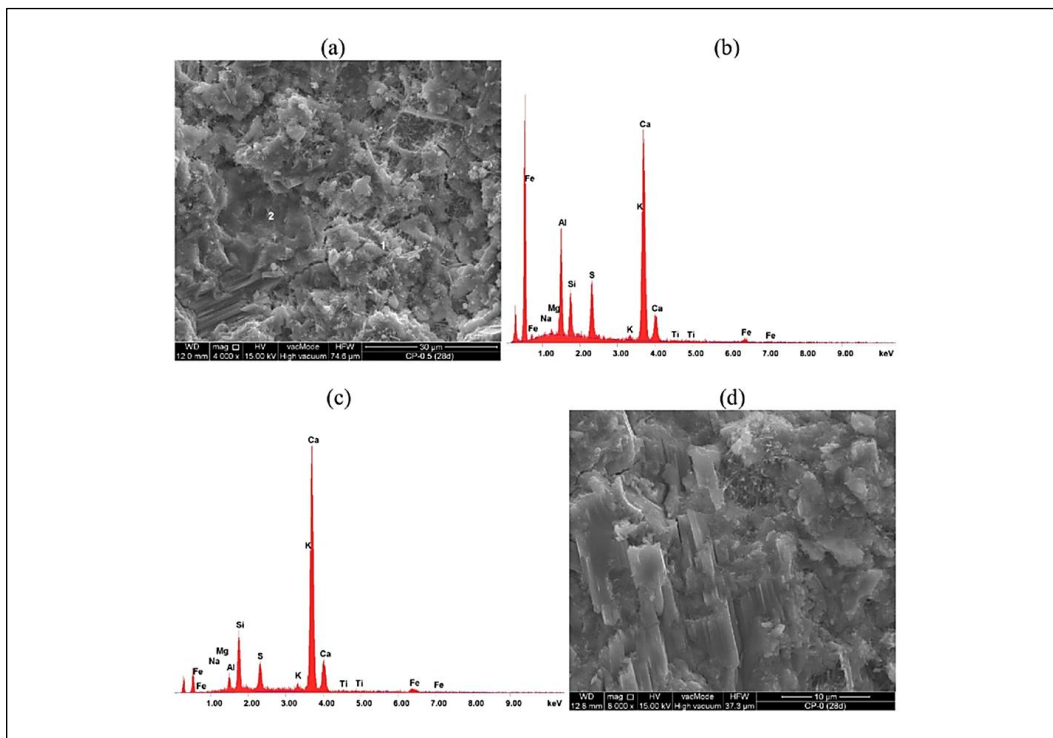


Figure 18. SEM and EDS images of 28 days which showing hydrated products of aluminosilicates and formed crystals of portlandite [72].

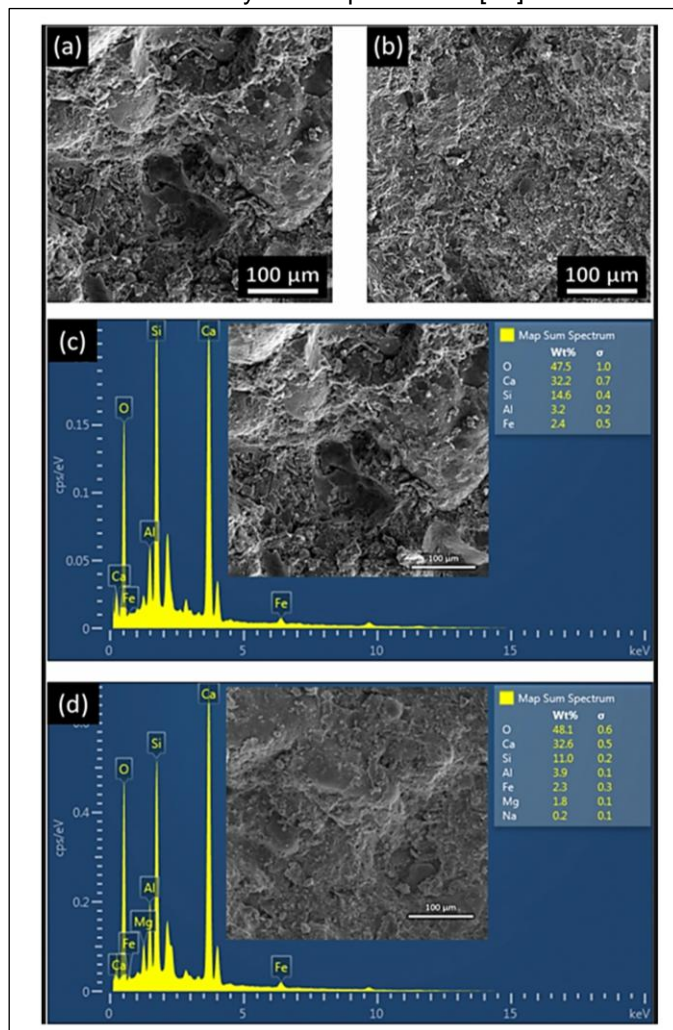


Figure 19. SEM images and EDS compositional analysis of the concrete core exposed different acid and bases [67].

Table 6. Synthesis of Microstructural Findings in BFRC.

Analytical Method	Observation	Interpretation	Reference
SEM + MIP	The critical pore diameter decreased from 116 nm to 60 nm when 0.2% basalt fiber was added	Basalt fibers refine the pore structure, limit water penetration and enhance freeze–thaw durability	[66]
SEM + XRD	Basalt fibers and steel fibers helped protect the hydration products even when the concrete was exposed to acidic and alkaline conditions	Fibers help stabilize the interfacial transition zone (ITZ) and reduce micro-defects	[67]
SEM	Fibers help connect and redirect cracks when the concrete is exposed to repeated loading	Redistribution of stress improves both fracture energy and ductility	[18, 51]
SEM + Micro-CT + DIC	Fracture energy increased by about 99%, ductility improved by about 110%, and the cracks became finer and more controlled	Continuous bonding between fibers and the matrix increases energy absorption	[18]
SEM	Dense microstructure and basalt helps the matrix stay more continuous and well-packed.	The combined action of basalt and steel fibers improves fatigue resistance	[68]
TGA/DTG	Lower material loss, slower CH breakdown, more bound water.	Thermal stability is improved and gel phases are better retained	[72, 73]
SEM + TGA	Withstands 700–1100°C cycles and control fails at 500°C	Basalt fibers enhance thermal resistance and help prevent spalling	[72]
XRD	Lower Ca(OH) ₂ peaks and stronger amorphous C–S–H rise	Silica from fibers helps form extra calcium silicate hydrate (C–S–H)	[72]
SEM–EDS	More chloride in control mixes vs BFRC and BF slows chloride entry	The bridging effect of basalt fibers limits chloride penetration and surface erosion	[71]
SEM + EDX	The smooth basalt fiber strands, ranging from 5–200 μm, are surrounded by Ca–Si–Al hydration products.	A strong fiber–matrix interface increases the overall strength	[69]

4. Role of Supplementary Cementitious Materials (SCMs) in Basalt Fiber-Reinforced Concrete

Adding supplementary cementitious materials (SCMs) to concrete is key for sustainable design the inclusion of supplementary cementitious materials (SCMs) to concrete is critical to sustainable design that is offering environmental and performance advantages. Fly ash, silica fume, GGBS, metakaolin, RHA and Alccofine are SCMs that partially substitute Portland cement by reducing the amount of carbon dioxide emissions and enhancing long-term strength through the effects of pozzolans and filler. The integrated effect of basalt fibers and SCMs further enhances the microstructure, enhances transferring loads and minimizes the brittle characteristic of the traditional concrete [33, 74–78].

4.1 Chemical and Physical Characteristics of SCMs

The various SCMs possess diverse varieties of properties such as fineness, mineral compositions, and pozzolanic reactivity, which influences the speed of hydration and densification of the matrices. Table 7 indicates the typical oxide content of SCMs. Other materials such as RHA and silica fume have large concentrations of silica and alumina that contribute to the creation of secondary hydration products. Unlike the calcium-rich structure of Alccofine enhances calcium silicate hydrate (C–S–H) to grow in the early stages.

Their disparity in oxide contents indicates the ability of RHA and Alccofine to collaborate. High amorphous silica is supplied in RHA and more aluminum and alumina is offered in Alccofine. They are combined to aid the hydration in various stages; Alccofine enhances initial strength and RHA enhances long-term densification.

Table 7. Typical SCM oxide components of typical basalt fiber-reinforced concrete [33, 74–78].

SCM Type	SiO ₂ (%)	Al ₂ O ₃ (%)	CaO (%)	Fineness (m ² /kg)	Key Function
Fly Ash	50–60	20–25	5–10	300–400	It has pozzolanic properties and also improves workability
Silica Fume	85–95	1–2	<1	15,000–25,000	It acts as a filler and provides high strength
GGBS	30–35	10–15	35–40	400–500	It has latent hydraulic properties and enhances durability
Rice Husk Ash	85–92	1–3	1–2	15,000–25,000	It contains reactive silica which helps refine the pores
Alccofine	35–40	12–15	45–55	4000–5000	Its ultrafine particles contribute to early strength development

4.2 Effect of SCMs on Hydration and Microstructure

SCMs influence hydration through the localization of C–S–H formation and alteration of chemical composition of pores structure. The BFRC with the addition of SCMs forms a dense C–S–H network reinforcing the interfacial transition zone (ITZ) between basalt fibers and cement matrix. Figure 20 shows SEM images of basalt fiber samples that are not subjected to high temperatures. Where in figure 20(a–b) samples that were not basalt had microcracks. On the contrary, basalt samples in Figure 20(c–d) had fewer cracks and a tighter structure because the fibers became bridges, slowing down the formation of the fractures. According to the SEM images, N-A-S-H gel and unreacted fly ash particles can be observed as well [36, 79–81].

Finely dispersed Alccofine particles facilitate C–S–H formation and RHA is added subsequently by reacting with calcium hydroxide [32, 82]. It is a two step process that minimizes the presence of free calcium hydroxide and enhances fiber-matrix bond that facilitates the transferring of stress. The SEM pictures of past literature reveal that BFRC modified by SCM contain less microcracks and have tight pores that translate to improved impermeability and strength even under extreme conditions [83, 84].

5. Mechanical Enhancement through RHA–Alccofine–Fiber Synergy

It is demonstrated that the synergistic effect of supplementary cementitious materials (SCMs) and fiber on the mechanical performance of concrete is due to microstructural refinement and greater fiber-matrix contact [10, 11, 85]. This section in the current review will only concentrate on the complementary effect of Rice Husk Ash (RHA) and Alccofine (AF) in basalt fiber reinforced concrete (BFRC), as indicated by the scope of the study.

5.1 Role of Rice Husk Ash (RHA) in Fiber-Reinforced Concrete

Rice husk ash (RHA) is a very reactive pozzolanic component when having a high amorphous silica content and it reacts with calcium hydroxide emitted during the hydration of Portland cement to produce more calcium silicate hydrate (C–S–H) gel. This response facilitates matrix thickening, pore shrinkage and decreases the amount of free Ca(OH)₂, which improves the mechanical and structural properties and performance of RHA-modified concrete [32, 76]. The positive outcomes of RHA such as decrease in porosity and enhanced durability are adequately reported in literature [86, 87]. It has been consistently reported in experimental research that a moderate dose of RHA (a level of about 5–10%) used to partially replace cement enhances compressive strength, and the best performance is normally achieved with a level of about 10% replacement as a result of pozzolanic and filler effects being additive. The maximum percentage of RHA used in blended cement systems is normally more effective in producing higher compressive strength compared to that of control mixes, but when used in excess, it decreases the strength, owing to dilution of cement [87, 88]. Certain studies have indicated strength increase at 10–15% [89, 91] replacement levels. The same tendencies exist in the case of flexural strength, with moderate levels of RHA integration (around 5–7.5%) increasing matrix continuity in terms of better particle packing and further C–S–H formation, whereas higher replacement levels (>10%), have negative impact on performance owing to lack of adequate binder content [92–93]. These results validate the use of RHA as an effective additive cementitious material in the optimal proportion, which has benefits of mechanical and durability and helps in the sustainability of cement substitution plans [94, 95]. Figure 21 indicates average values of strength improvement of RHA replacement percentages.

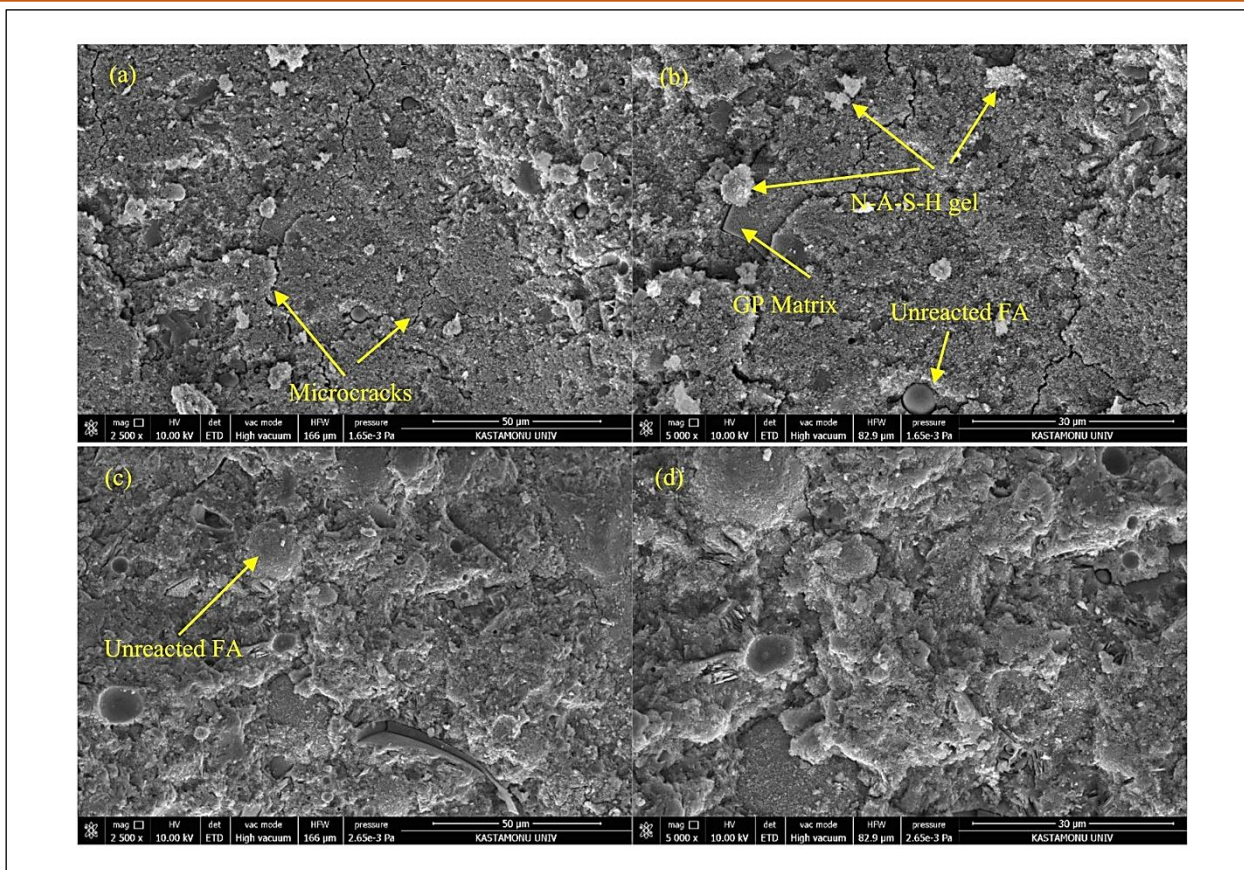


Figure 20. SEM images of SCM–fiber–matrix interactions showing densified ITZ [80].

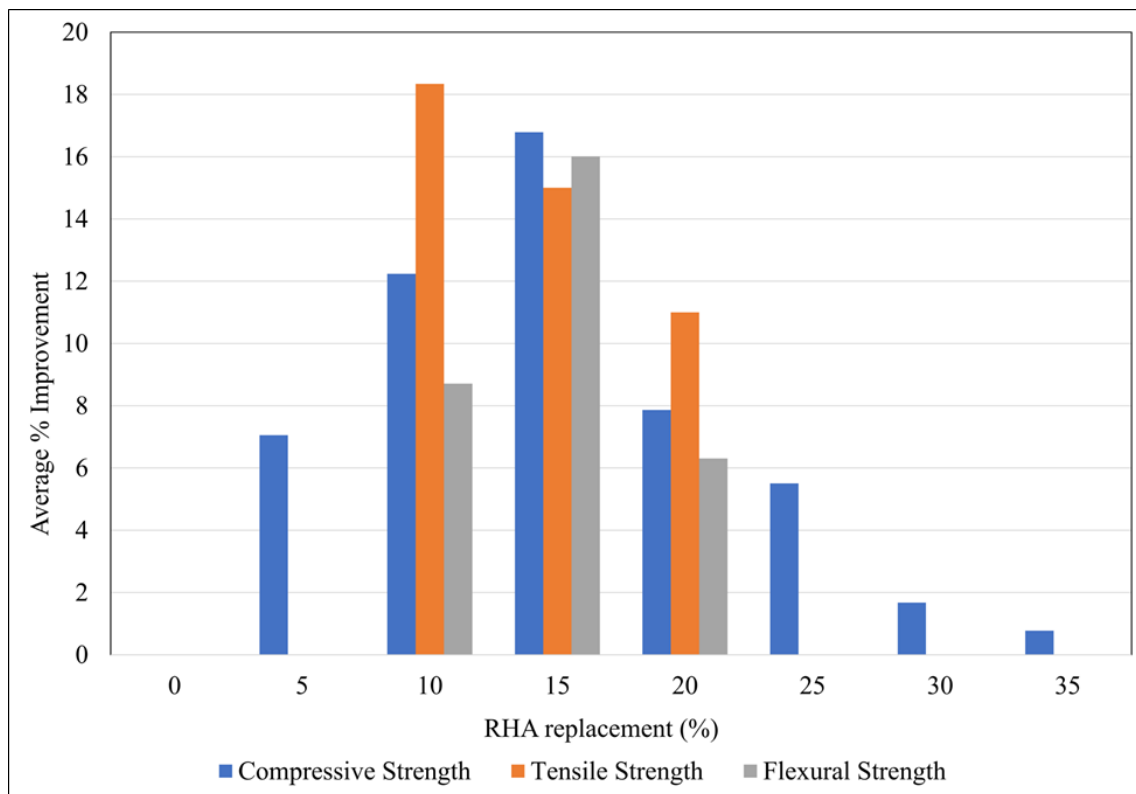


Figure 21. Mean strength changes values of RHA replacement percentage [93–95].

RHA is used in fiber-reinforced cementitious systems to develop a more dense interfacial transition zone (ITZ), which improves the anchorage of fibers and the crack-bridging capabilities [93, 94]. Research on

high performance fiber-reinforced concrete with RHA indicates enhanced tensile strength, and ductility following better bonding between fibers and the matrix and slower crack propagation [94-96].

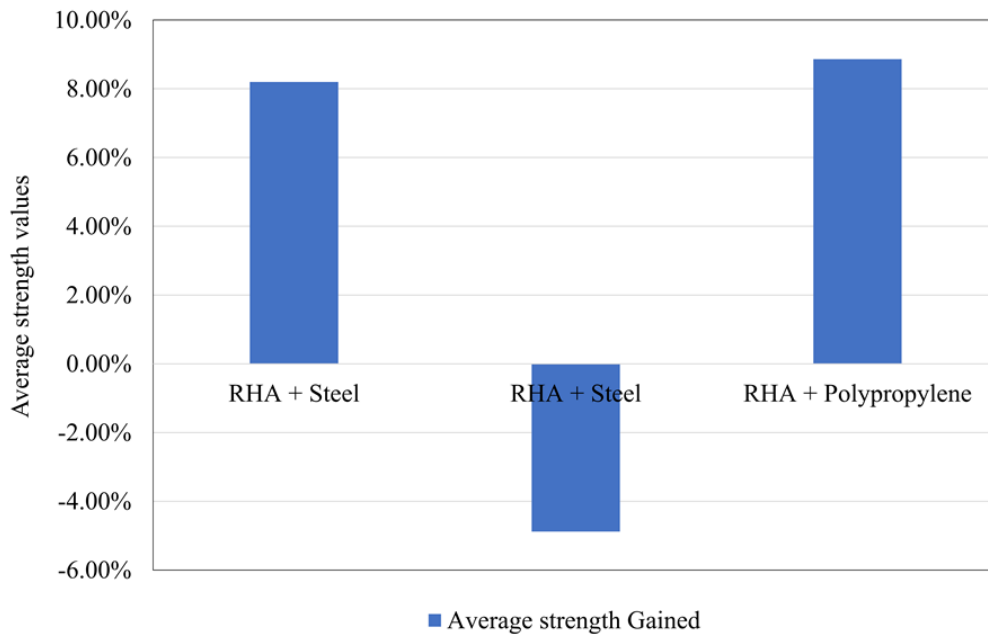


Figure 22. Strength characteristics of the best RHA-fiber reinforced concrete composites [97-100].

RHA is also better in enhancing durability through refinement of pore structure, decreasing permeability, and increasing resistance to chloride ingress. It has been experimentally demonstrated that RHA with steel fibers enhance the strength of 10% replacement with enhanced fiber-matrix covalency [94]. Carefully alkali resistant glass fiber has been reported to exhibit low synergy, with a small compressive gain and tensile reduction since it is not chemically compatible with the RHA modified matrix [99]. The polypropylene fibers have been found to perform better with compressive and flexural gains at low dosage (0.25–0.4%) attributed to interaction of fiber hydrophobicity with RHA water-demand characteristics [100] at lower dosages as demonstrated in Figure 22. RHA-induced refinement in the matrix of basalt fiber-reinforced concrete (BFRC) increases fiber-matrix interaction, interlock, and toughness and post-cracking behavior [101, 102] further. Moreover, the use of RHA gives some benefits in the environment through the valorization of farm waste, decreasing the use of cement, and decreasing the carbon footprint of concrete [103, 104].

5.2 Role of Alccofine in Fiber-Reinforced Concrete

Alccofine is a fine slag-based supplementary cementitious material (SCM) with a high content of glass and a very fine particle size that contributes to the improvement of hydration kinetics and high early-age reactivity because of a large surface area to react [82, 105]. Post-compared to traditional slag materials, Alccofine can greatly enhance the rapid development of the early strength with strong nucleation and filler effects and result in the creation of dense calcium-silicate-

hydrate (C-S-H) network and refined microstructure at young ages [105, 106].

In spite of the fact that there has been limited direct experimental research on the incorporation of Alccofine in basalt fiber-reinforced concrete (BFRC) yet available data on the use of Alccofine in cementitious systems and fiber-reinforced concrete (FRC) show that incorporation of this substance in concrete improves compressive and split tensile strength mainly by increasing density of the matrix, refining the pore structure, and enhancing the interfacial transition zone (ITZ) [107, 108]. Due to its small particle size and large content of glassy phase, Alccofine enhances early hydration through filler and nucleation schemes to form a compact C-S-H network that enhances stress transfer across the fiber-matrix interface in fiber-reinforced systems [33, 109, 110]. Experiments of FRC and high-performance concrete with the use of ultrafine SCMs further indicate that moderate levels of Alccofine replacement (usually $\leq 10\%$) increase early-age strength without degrading later-age mechanical performance as the material helps the fibers to achieve continuity and anchoring of fibers [107, 109, 111]. According to these developed mechanisms, Alccofine will be promising to interact well with basalt fiber reinforcement but a systematic experimental validation of OPC based BFRC is an open research gap. Figure 23 shows the compression strength of Alccofine with various volumes of fibers.

5.3 Synergistic Effects of RHA and Alccofine in BFRC

The synergy in the effect between rice husk ash (RHA) and Alccofine is because both exhibit opposite reactivity patterns.

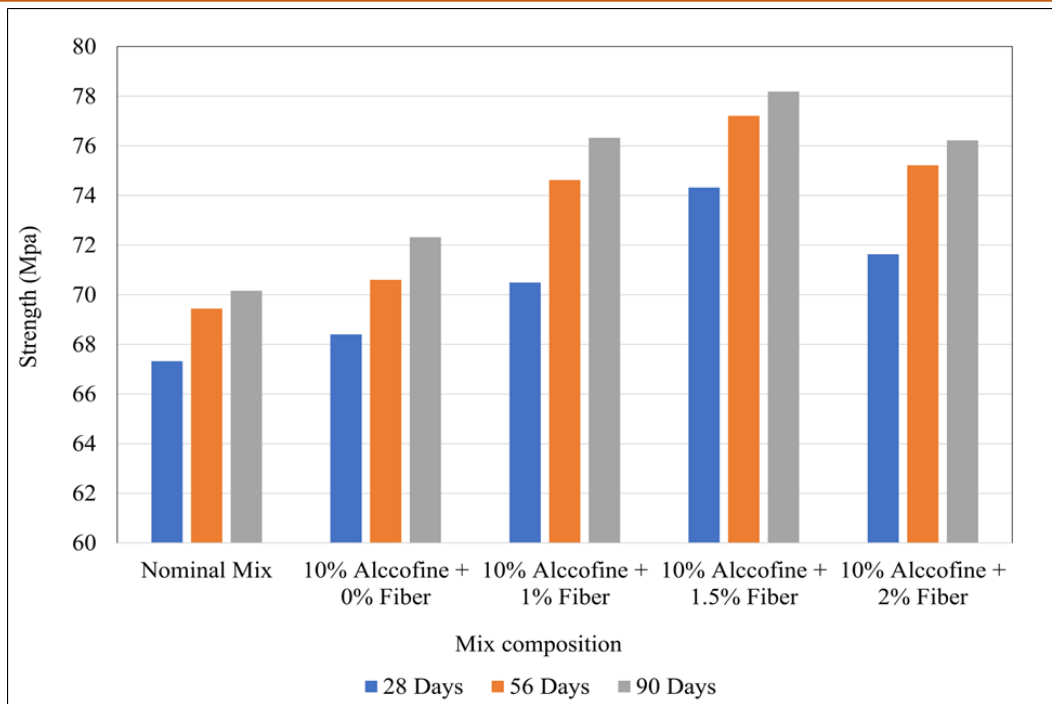


Figure 23. Compression strength for alccofine with basalt fiber [112].

Table 8. The trends of reported strengths and predominant processes in the basalt fiber-reinforced concrete with various types of supplementary cementitious material (SCM) systems

SCM system	Fiber content	Strength trend	Dominant mechanism	References
RHA-modified concrete	Basalt fiber ($\leq 1.0\%$)	Increase in compressive, tensile, and flexural strength	Pozzolanic reaction of amorphous silica, secondary C–S–H formation, pore refinement, improved crack resistance	[24, 37, 113–116]
Alccofine-modified concrete	Basalt fiber ($\leq 1.5\%$)	Significant early-age strength enhancement	Ultrafine filler effect, accelerated hydration, dense C–S–H network, strengthened ITZ	[49, 56, 82, 117]
RHA + Alccofine (binary SCM system)	Basalt fiber (inferred)	Expected improvement in early and long-term strength	Complementary early hydration (Alccofine) and long-term pozzolanic activity (RHA), refined pore structure, denser ITZ, enhanced fiber–matrix bonding	[83, 118]

RHA adds long term pozzolanic action in form of gradual interaction of amorphous silica with calcium hydroxide liberated during cement hydration and resulting in sustained development of secondary C–S–H, and progressive pore refinement at later ages [113–115]. Conversely, Alccofine is a better early-age hydrator due to its ultrafine particle size, high level of glass and strong nucleation and filler effects, which hastens the cement hydration process and leads to early densification of the matrix [82, 115].

Direct experimental research on RHA-Alccofine mixed concrete is still scarce in the existing literature, but the synergy between them is one that can be assumed through the use of research on RHA mixed concrete systems and Alccofine-modified cementitious composites. The past research results reveal that multi-

SCM systems with complementation by early- and late-sensitive reactivity enhance particle packing, optimize pore structure, and result in a denser interfacial transition zone (ITZ) when compared to single-SCM systems [10, 28]. This type of microstructural refinement is especially beneficial in fiber-reinforced concretes, in which densification of the matrices promotes the anchorage of the fibers and the effectiveness of stress transfer [12, 31]. In turn, the polished cement scaffolding generated by the RHA-Alccofine systems is likely to enhance fiber-matrix bondage in BFRC, which promotes crack-bridging proficiency, and after-cracking in a variety of curing ages. Table 8 cites the prevailing mechanisms which dominate the development of strength of basalt fiber-reinforced concrete by incorporating other SCM systems, where ultrafine SCM systems promote early-

age of performance through speeding up hydration, whereas silica-rich SCM systems promote long-term strength through pozzolanic C–S–H formation and enhanced fiber-matrix interactivity.

These trends indicate that compensation levels of SCM replacement and fiber dosage must be optimized such that the highest mechanical benefits are attained without affecting the workability.

5.4 Sustainability and Performance Implications of RHA–Alccofine Systems

In addition to the mechanical improvement, by using rice husk ash (RHA) and Alccofine jointly, the cementitious systems can achieve considerable sustainability improvements through the lessening of clinker consumption and the repurposing of industrial and agricultural wastes. RHA is a by-product of rice milling waste, whereas the Alccofine is an ultra-fine slag-based material, which is recovered as a by-product of metallurgical byproducts, so both materials are resource-friendly due to the utilization of wastes and a higher level of resource efficiency [20, 24, 28]. It has been reported that with blended cement and high-performance cement systems, a mix of silica-rich and calcium-rich SCM that replaces OPC by a percentage of about 30–40% can lead to significant OPC content reduction in the mix, leading to considerable embodied CO₂ reduction and energy demand, depending on mix design and replacement level [7, 21, 28]. Additionally,

enhancements in durability and mechanical performance, including decreased permeability, enhanced microstructural stability and increased crack resistance, increase service life and reduce lifecycle maintenance needs, therefore, making the overall sustainability better despite incremental material costs of fibers and SCMs [20, 23, 24].

5.5 Comparative Assessment and Sustainability Implications

The RHA–Alccofine blend has a more balanced hydration process than a typical binary SCM system does. The combination of Alccofine-RHA is both early and long-term beneficial as it allows to achieve a higher microstructural refinement even at lower replacement rates of binder, 10–20% [107, 119]. The RHA + Alccofine blend has been found to be more overall strength and durable than the common binary mixes like fly ash + silica fume, GGBS + silica fume, RHA + silica fume, and RHA + GGBS [120]. RHA also adds long-term pozzolanic reactivity to improve the strength of later ages because of the amorphous silica content [121], and Alccofine enhances the strength development at early age because of its ultrafine particle size and high reactivity [38, 122]. This hybrid combination has been experimentally demonstrated to enhance compressive strength and durability, as shown in Figure 24 and is appropriate in high-performance concrete, which needs early demolding and fast construction.

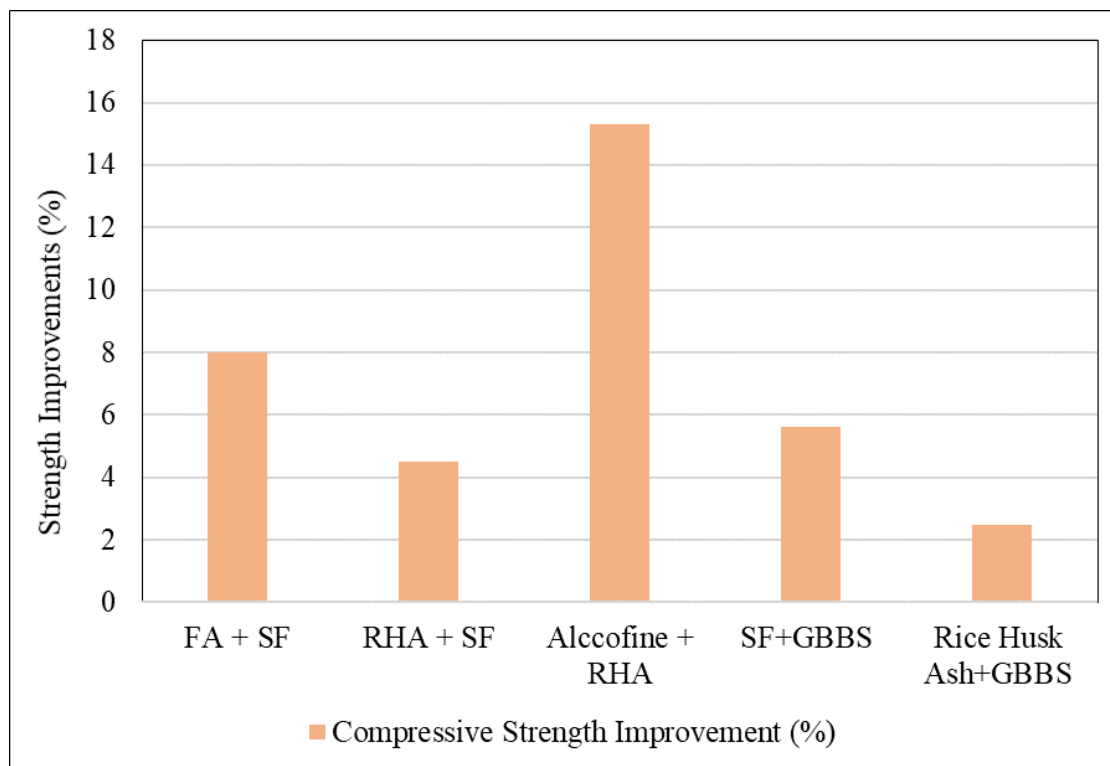


Figure 24. Comparison of binary SCM systems on compressive strength improvement [120, 123–126].

Table 9. Trends of Mechanical Strength Enhancement through Interaction of SCMs and Fibers

SCM Type	Fiber Volume (%)	Compressive Strength Improvement (%)	Reference Trend
Silica Fume (SF)	1.0–1.5% BF	28–65% increased	SF produces secondary C–S–H gel which densifies ITZ and strengthens fiber–matrix bond [31, 129].
Fly Ash (FA)	1.0% BF	Strength enhancement at 20–30% FA	FA improves dispersion and refines pores which enhances long-term strength. High FA lowers early-age strength [17, 130].
Rice Husk Ash (RHA)	0.25% PP, 0.5–2% GF	10–25% increased	RHA forms additional C–S–H gel which densifies microstructure and enhances crack control [83, 97, 113].
Alcofine (AF)	1.0–1.5% SF	47% increased	AF increases early-age reactivity which densifies ITZ and strengthens fiber anchorage [131].
GGBS	0.5–1.5% BF	Improvement with 30–40% GGBS	Hydraulic C–S–H formation and pore refinement enhance strength [132, 133]
Metakaolin (MK)	0.5–1.0% BF	25–30% increased	MK forms C–S–H and C–A–S–H, producing a dense ITZ and improved bond [134, 135].

These findings prove that the Alcofine–RHA mixture strengthens and improves the wear and tear of BFRC, besides decreasing the environmental impact by decreasing the clinker usage. The hybrid system works at various water-cement ratios and under varying curing conditions and thus it fits in high performance and sustainable infrastructure. In addition to mechanical gains, SCMs have been found to greatly minimize the environmental impact of concrete production. RHA, an agricultural waste product in form of the byproduct of rice milling and Alcofine, which is produced out of slag, use agricultural and industrial wastes, which corresponds to the concept of a circular economy. OPC can be reduced by up to 40% by incorporation of these SCMs in BFRC, therefore, reducing CO₂ emissions and embodied energy [76, 127, 128]. Other SCM advantages include the high long-term sustainability due to long duration, low maintenance requirement, long service life and the overall offset of the initial cost of the fibers and SCM processing [36]. Table 9 reveals that the alcofine containing fiber enhances the strength better than the other SCMs and the alcofine enhances the early strength. Then, the best alternative is to enhance the long-term strength RHA as it is also an agricultural waste.

6. Combined Effect of Rice Husk Ash (RHA) and Alcofine in Basalt Fiber Reinforced Concrete (BFRC)

Combining rice husk ash (RHA) with Alcofine in the basalt fiber-reinforced concrete (BFRC) increases its strength, durability and environmental performance. Even though all the materials used are pozzolanic or hydraulic in nature, the complementary chemistry and particle properties get between them to create a greater

synergistic effect. Amorphous silica (which is present in large amounts in RHA) reacts slowly with calcium hydroxide to produce more C–S–H gel, crystallizing the pore structure and increasing long-term strength [136, 137]. Alcofine is a calcium and alumina-based ultrafine slag, which is capable of reacting very quickly and facilitating the quick development of C–S–H and calcium aluminate hydrates (C–A–H) in the hydration process [138]. Alcofine is also used to accelerate early hydration to form a dense matrix that maximizes the reactivity of RHA by trapping silica in a fined pore structure and maximizing the second hydration efficiency. Such action of synergy enhances the interfacial transition zone (ITZ) and greatly enhances the performance of BFRC. The mechanism of the interaction can be described in the following way:

1. Cement + Alcofine → primary C–S–H + C–A–H (gives early strength)
2. C–H + RHA (SiO₂) → secondary C–S–H (helps densify the mix over time)

The two reactions form a hybrid long-lasting microstructure which is dense. Figure 25 demonstrates the pore refinement, ITZ densification, and enhanced basalt fiber-matrix bonding through C–S–H and C–A–H formation coupled with slower secondary formation pore refinement, which is contributed by rice husk ash. It is represented through mechanistic knowledge found in the literature of single and dual-SCM systems, instead of being experimentally determined of the ternary RHA–Alcofine–BFRC system. In this conceptual framework, Alcofine facilitates early hydration, to produce primary C–S–H and C–A–H, and at later ages, RHA facilitates secondary C–S–H to form, which in combination stimulates the densification and optimization of the interfacial transition zone (ITZ).

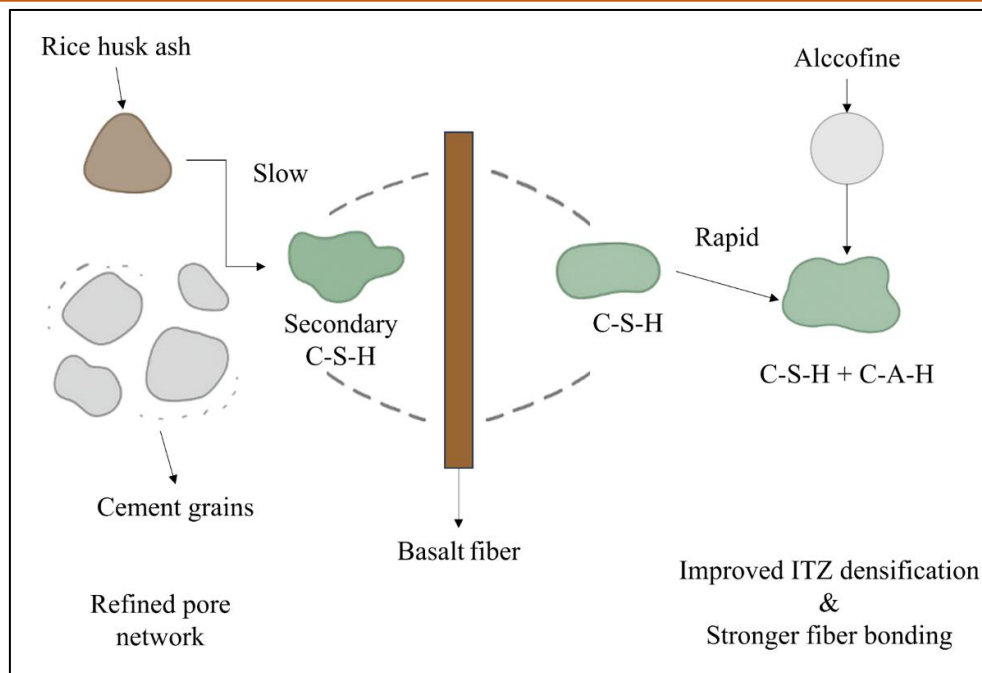


Figure 25. Schematic representation of the complementary hydration and pozzolanic mechanism of the rice husk ash and Alccofine in basalt fiber-reinforced concrete.

The number is schematic and obtained through mechanistic observations observed with the similar systems because there are no such experimental measurements of the SEM/XRD of the ternary OPC-BFRC system.

The quality of fiber-matrix bond is a very critical performance of the fiber-reinforced composites. At BFRC, RHA and Alccofine have a strong influence on fiber-matrix interactions. Ultrafine Alccofine particles occupy micro-voids, which are between basalt fibers, and RHA provides extra C-S-H gel that sticks to the fiber surfaces. The combination of these results in a thick and high bonding interfacial transition zone (ITZ), which lessens the microcracking and fiber pull-out [96, 109]. In the recent studies, SEM observations have shown that transitions between fibers and matrices were smoother, and less interfacial voids are observed with the employment of both SCMs. This reinforced ITZ increases the transfer of stress between fibers and matrix, thus increasing the post-cracking load capacity, and toughness in general, of BFRC [66].

6.1 Durability and Long-Term Performance Insights

The BFRC performance of RHA Alccofine type is under control of matrix densification, chemical stability, and crack control. Repeated pozzolanic reaction of RHA leads to the formation of C-S-H which fills microcracks and further diminishes permeability [121]. To increase sulfate and acid resistance, Alccofine reacts with $\text{Ca}(\text{OH})_2$ and produces stable hydration products [33]. Basalt fibers also slow down crack propagation and reduce thermal and drying cycle induced stresses [36].

A combination of RHA and Alccofine is anticipated to greatly elevate longevity, and it is electronic that trends will show that water ingestion levels will decline by about (20–30%), chloride internalization will decline by about (40–60%) and sulfate-associated harm will decline by comparison to single-SCM systems [122, 139]. These enhancements are due to the pore refinement and Alccofine to ultra fine particle packing and accelerated hydration that also improves the resistance to carbonation and high strength in the long term [121, 122].

In addition to performance, this hybrid system encourages sustainability by utilizing agricultural and industrial wastes hence lowering the cement demand and the resultant CO_2 emission. Environmental compatibility is further enhanced by the fact that the basalt fiber production does not need much energy (which is relatively low) [77, 140]. Workability is also increased with better particle packing, and less superplasticizer is required as well as uniformity in fiber dispersion. Therefore, BFRC made by Alccofine-RHA demonstrates active perspectives of long-term high-strength usage in marine constructions, bridges, and high-rise buildings [94, 109]. Table 10 shows that hybrid SCM basalt fiber systems are always superior to single-component modifications because densification of the matrix created by pozzolanic or hydraulic SCMs supplement crack regulation caused by fibers, hence, the results are compared by enhancements in strength and durability simultaneously.

Table 10. Strength and durability performance of concrete that contain supplementary cementitious materials and basalt fibers reported

System Studied	SCM / Fiber Content	Strength Change (%)	Durability Indicator	Key Observations	Reference
OPC + RHA	RHA 10–15%	+10 to +25% increase in compressive strength and flexural strength	Decreases Permeability, water absorption (15–30%)	Pozzolanic reaction refines pore structure and ITZ	[141, 142]
OPC + Alccofine	Alccofine 8–12%	+12 to +30% early-age compressive strength gain	Decreases Chloride penetration (30–50%)	Filler + latent hydraulic effects enhance early densification	[33, 142]
OPC + Basalt Fiber	BF 0.1–0.5% vol.	+5 to +15% mainly flexural strength improvement, little change in compressive strength	Crack width reduction, increases energy absorption	Fibers bridge cracks and delay propagation	[16, 143]
OPC + RHA + BF	RHA + BF	+15 to +30% significant flexural strength improvement	Decreases Permeability, improved crack resistance	Combined pozzolanic densification and crack control	[144]
OPC + Alccofine + BF	Alccofine + BF	+15 to +35% both flexural and compressive strength improved	Decreases Chloride ingress, sulfate damage	Synergy between fine SCM and fiber reinforcement	[115]

6.1.1 Sulfate, Carbonation, and Alkali-Silica Reactions

Pozzolanic reactions of RHA lead to lessening the amount of free calcium hydroxide in the cement matrix, which forms more C–S–H gel. Theoretically, this consumption of CH can inhibit the development of expansive ettringite in the presence of sulfate-rich conditions to enhance sulfate resistance [145, 146]. The early hydration of the cement and the fine particle packing can also accelerate the densification of the matrix by Alccofine which might further decrease the ingress of sulfates ions [147, 148]. Nevertheless, the direct experimental indication of the sulfate resistance of ternary OPC–RHA–Alccofine BFRC is not available as yet, which is a crucial gap to be filled in the future research.

Carbonation is the diffusion of CO₂ into concrete and combining it with calcium hydroxide to form calcium carbonate, which may reduce the PH, thereby weakening the bond between the fiber and the matrix. Pozzolanic activity of RHA lowers CH content, which could affect kinetics of carbonation [149]. Although the densified matrix generated by using the combination of RHA and Alccofine should decrease the rate at which CO₂ enters the system, no explicit values of the carbonation depth of the ternary BFRC systems are found to support the point [150].

The amorphous silica of RHA can react with alkalis contained in cement, which in theory can form expansive gels when reactive aggregates are available [151]. Nevertheless, this risk can be minimized by the

pozzolanic intake of alkalis by RHA which decreases the concentration of free alkalis in the pore solution [151]. Alccofine is low in alkalis and does not add to ASR [152]. Although this is theoretical knowledge, experimental research assessing ASR in ternary RHA–Alccofine BFRC has never been conducted and this indicates the necessity of conducting specific tests, particularly in aggressive conditions or in cases where reactive aggregates are involved. As shown in Table 11, it can be seen that Alccofine mainly dominates early-age performance due to accelerated hydration, while rice husk ash dominates long-term strength and durability due to long-term pozzolanic reactions with basalt fibers playing a supplementary role in controlling cracks at later ages.

Overall, although mechanical reasoning indicates that it is possible to enhance the sulfate resistance, carbonation, and mitigation of ASR improvements in ternary OPC–BFRC systems, they are still qualitative phenomena and experimental validation of these phenomena in the future is needed to measure the effects of all these durability phenomena.

6.2 Microstructural Characteristics and consideration of RHA-Alccofine Blended BFRC.

Rice husk ash (RHA) is a very reactive pozzolanic substance that contains large amounts of amorphous silica that reacts with the calcium hydroxide that is produced when the cement is hydrating to produce secondary calcium silicate hydrate (C–S–H) gel.

Table 11. Age-related contributions of additional cementitious materials and basalt fibers of the influence on the formation of strength and durability

Curing Age	SCM Contribution	Observed/Expected Effect	Mechanism	Supporting References
7 days	Alccofine	Early compressive/flexural strength gain	Accelerates hydration → faster formation of primary C–S–H and C–A–H	[33]
7 days	RHA	Minimal effect	Slow pozzolanic reaction; low early reactivity	[97]
28 days	Alccofine + RHA	Moderate increase in strength and durability	Alccofine densifies matrix; RHA starts contributing secondary C–S–H	[33, 97]
28 days	Fiber (BF)	Improved crack bridging and ductility	Fibers start controlling microcracks; stress transfer improves	[48]
90 days	RHA	Significant increase in long-term strength and durability	Continuous pozzolanic reaction; pore refinement; ITZ densification	[139]
90 days	Alccofine	Stabilization of matrix; minor additional contribution	Early hydrates maintain matrix density; less effect than at early age	[33]
90+ days	RHA + Alccofine + BF	Optimized combined performance	Matrix densification + strong ITZ + fiber bridging → high toughness, reduced permeability	[33, 36, 139]

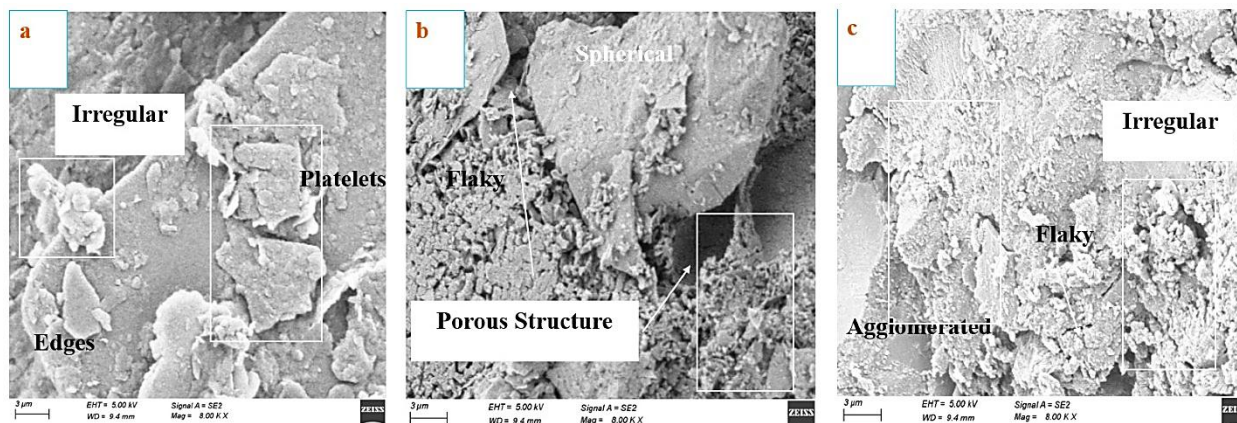


Figure 26. SEM micrographs of RHA blended concrete [154].

This pozzolanic activity results in a refined microstructure of RHA-blended cementitious system and contains lower porosity and a denser cement matrix. RHA is also an efficient micro-filler at optimum levels of the replacement level (around 10%), which enhances the particle packing, as well as interfacial transition zone (ITZ). Nevertheless, an increase in the RHA contents can lead to unfinished pozzolanic reactions and microstructural heterogeneity at the local level [153]. SEM and XRD analyses reveal that incorporation of RHA lowers plate-like crystals of $\text{Ca}(\text{OH})_2$ and favors the formation of plate-like crystal C–S–H gel, which forms a tighter and smaller microstructure. Adding effects of these make it strong and durable at the optimum replacement levels [154]. Figure 26 & 27 presents the SEM and XRD images of RHA blended concrete which displays the porous structure and reaction with concrete.

Alccofine is a slag-based ultrafine cementitious material, which has a dominant effect on the formation of the microstructure at an early age. Its very fine particle size and a high level of glass content allow strong filler and nucleation which accelerates the hydration as well as fast C–S–H formation. In microstructural analyses of Alccofine-modified concrete, it is possible to state that a dense paste has less connectivity among pores and a fine interfacial transition zone (ITZ), especially at the relatively young age of curing [155]. The figure 28 shows, the SEM and XRD image of Alccofine blended concrete which is a pointer of C–S–H gel, dense C–S–H, and voids.

A multi-scale densification occurring between RHA and Alccofine is deductible when the two are applied jointly.

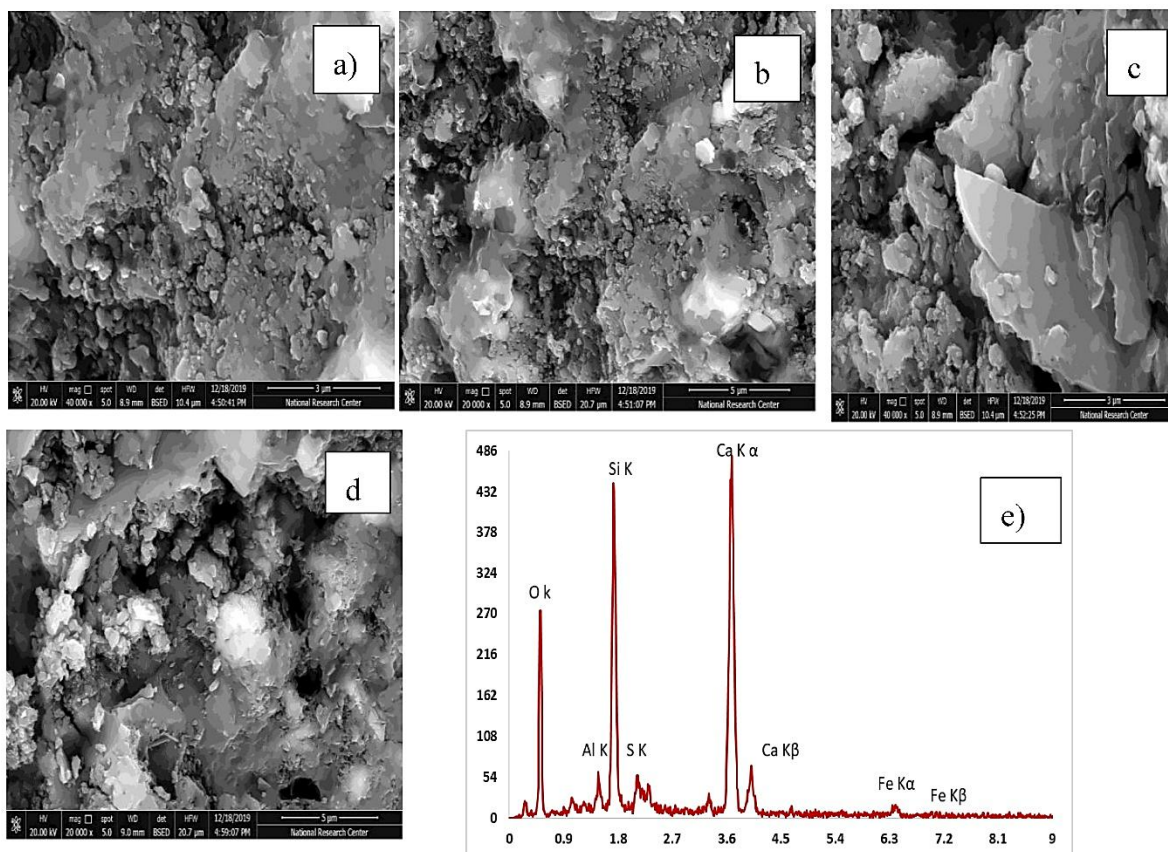


Figure 27. SEM and EDX images for rice husk ash [155]

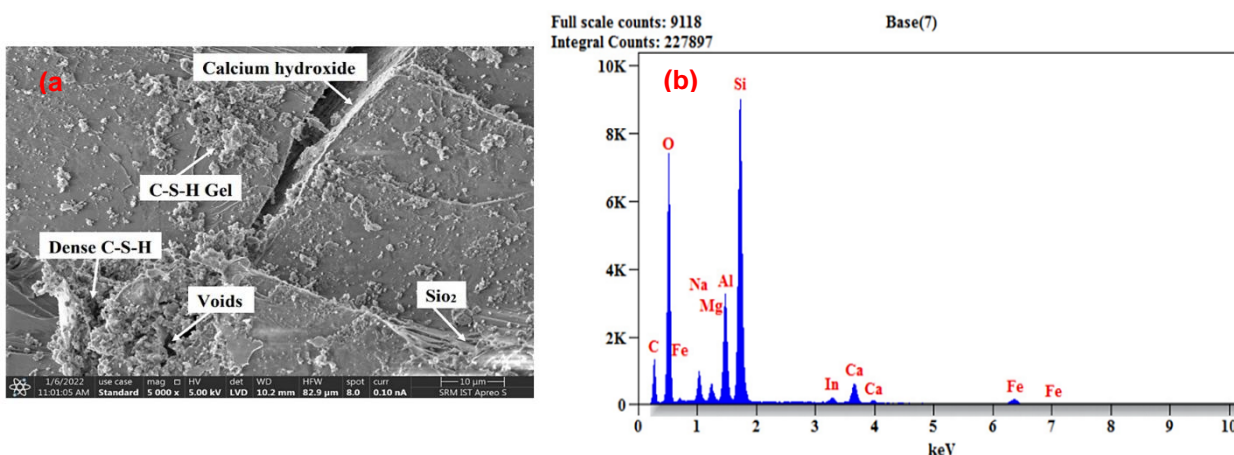


Figure 28. SEM and XRD image of Alcofine [156].

Alcofine helps in packing of early-age matrix and makes it grow faster in hydration, whereas RHA increases the secondary C–S–H formation and refining of the pores in later ages. Such a balancing action is predicted to yield a more homogeneous and compact cementitious matrix than that of systems using either of the two independently [111, 123, 125].

The fiber performance in basalt fiber reinforced concrete is highly dependent on the quality of the surrounding matrix and the fiber-matrix ITZ. Literature on basalt fiber reinforced concrete suggests that a higher density of the cementitious matrix leads to an even thinner and more powerful ITZ, a higher mechanical interlock, and greater stress transfer between the fibers

and cementitious matrix. The optimized microstructure that is generated by the incorporation of RHA and Alcofine will, therefore, be beneficial in the fiber anchorage and crack-bridging efficiency of BFRC [16, 125, 153–156].

6.2.1 Interfacial Transition Zone (ITZ) Refinement of RHA and Alcofine

The fine and reactive particles of RHA and Alcofine are very fine, which enhances the interfacial transition zone (ITZ) amongst the paste, aggregates, and fibers enormously. The amorphous silica and the high-surface-area particles of RHA are concentrated

within cement-aggregate interfaces, which refines the microstructure and decreases the ITZ thickness by means of a combined pozzolanic and packing effect [91, 157]. Equally, the ultrafine slag-based particles at Alccofine serve as micro-filler and nucleation sites, which enhances the formation of dense hydrate at interfaces. A near-identical ITZ with uninterrupted C–S–H coverage is observed in the systems with ultrafine SCMs like silica fume and Alccofine [107, 158]. RHA is used in ternary RHA–Alccofine mixture, with RHA providing more silicate gel and Alccofine providing silicate–aluminat hydrates in combining to form a smoother and denser ITZ. This polished interface enhances connections with aggregates and fibers and eliminates weak areas that are likely to develop cracks [91, 159].

6.2.2 C–S–H Gel Densification of RHA and Alccofine

Both RHA and Alccofine hastens and prolongs cement hydration by consuming portlandite and developing more C–S–H gel. The presence of high SiO₂ in RHA reacts with Ca(OH)₂ to form secondary silicate gel hence densifying the microstructure of concrete by filling the pores [91, 157]. On the same note, the reactive calcium-silicate composition by Alccofine encourages fast hydrate polymerization. The study of pozzolan-enhanced systems by SEM demonstrates that the systems have compact, interlocking C–S–H networks and with a minimum number of voids [107, 159]. As an illustration, concrete with 10% Alccofine plus another SCM has a well pressed C–S–H complex that fills the pre-existing capillary pores [91, 159]. The same process occurs in RHA-Alccofine blends: the two SCMs provide reactive silica (Alccofine also provides CaO and Al₂O₃) and result in an increase in both portlandite utilization and in the quantity of secondary hydrates. As a result, the ternary system forms a very polymerized and dense C–S–H structure, which is always related to fine pore structure and enhanced strength in relation to OPC systems [159].

6.2.3 Crack Control and Reduction in Porosity of RHA and Alccofine

RHA and Alccofine largely decrease pore connectivity and total porosity through the process of packing and filling of effects. Their ultrafine particles work on various scales: nano-scale C–S–H that is produced in the reaction of pozzolans closes micropores, whereas unreacted RHA and Alccofine grains prevent capillary channels. The experimental studies cite less sorptivity and chloride permeability in concretes that contain these SCMs, which confirm that it has a less permeable matrix [91, 159]. Microscopic examination also demonstrates a significant reduction in the number of cavities in SCM-altered pastes as opposed to the simple cement. As an example, SEM images of matrices which are based on Alccofine show a high density with few microcracks [107]. Equally, it is reported that ultrafine RHA can decrease the average pore size and refine the pore structure especially around interfacial regions [91, 159]. This gives rise to a homogeneous low-porosity matrix that is less prone to shrinkage cracking. Together with basalt fibers, this dense matrix inhibits the early formation of microcracks and strains extending cracks to take winding routes through densely C–S–H, and thus it dissipates energy through smaller cracks apertures.

6.2.4 Fiber–Matrix Bonding and Crack Bridging of Basalt fibers

Basalt fibers need a high level of bonding with cementitious matrix to be effective in improving toughness. The microstructure of RHA and Alccofine is refined and enhances adhesion between the fibers and the matrix as SEM images reveal the tight bonds between basalt fibers and no observable interfacial gaps and this is a sign of successful wetting and transfer of stress [158]. This firm bond enhances crack-bridging and regulated fiber pull-out allowing the fibers to take in fracture energy and retard crack propagation.

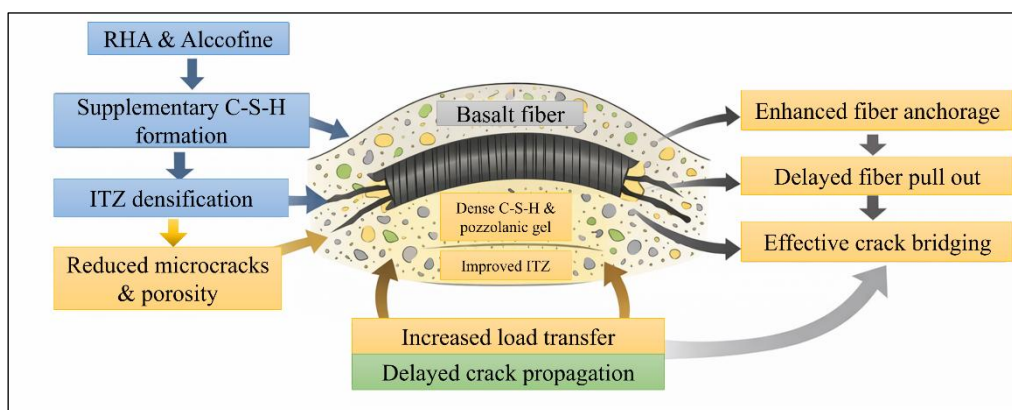


Figure 29. Figure showing the schematic diagram of synergistic interaction between RHA, Alccofine and basalt fibers resulting in densification of the ITZ, enhanced fiber anchorage and slowing of crack propagation.

Table 12. Summary of combined hydration, microstructural, mechanical, durability, and sustainability mechanisms in RHA–Alccofine–basalt fiber–reinforced concrete.

Aspect	Key Observation	Mechanism / Explanation	Supporting References
Early-age hydration	Rapid strength development	Alccofine reacts quickly to form primary C–S–H and C–A–H, accelerating hydration	[107]
Long-term hydration	Continuous strength gain	RHA provides slow pozzolanic reaction, consuming Ca(OH)_2 and forming secondary C–S–H	[136]
Hybrid hydration mechanism	Balanced early and long-term performance	Early Alccofine hydration densifies matrix, enhancing RHA reactivity at later ages	[107, 136]
Matrix densification	Reduced porosity and refined pore structure	Combined filler effect and secondary C–S–H formation produce compact microstructure	[107, 160]
ITZ refinement	Thinner and stronger ITZ	Ultrafine Alccofine fills micro voids and RHA supplies additional silicate gel	[107, 161]
Fiber–matrix bonding	Improved fiber anchorage and reduced pull-out	Dense ITZ and C–S–H coverage enhance mechanical interlock around basalt fibers	[43, 107, 136]
Crack control	Delayed crack initiation and propagation	Dense matrix + strong fiber bonding enhances crack-bridging efficiency	[153, 156]
Durability – permeability	Likely lower water absorption	Pore refinement and continuous C–S–H filling reduce connectivity	[108, 160]
Durability – chloride resistance	Likely reduced penetration	Dense microstructure and fiber crack control limit ion transport	[108, 162]
Durability – sulfate/acid resistance	Improved resistance and reduced damage	Reduced Ca(OH)_2 and formation of stable hydrates	[146, 147]
Thermal and shrinkage stability	Improved crack resistance	Basalt fibers act as stress barriers; SCMs stabilize hydration products	[146, 147, 163]
Workability and fiber dispersion	More uniform fiber distribution	Improved particle packing reduces clustering and superplasticizer demand	[56]
Sustainability impact	Reduced cement consumption and CO_2 emissions	Use of agricultural (RHA) and industrial (Alccofine) by-products	[86, 159]
Overall BFRC performance	High strength, durability, and sustainability	Synergistic interaction of RHA, Alccofine, and basalt fibers	[56, 107, 136]

The fibers are trapped within the thickened RHA-Alccofine-modified matrix by the maximum possible pull-out resistance and inhibiting early debonding. The synergistic effect of matrix densification and the increased fiber bonding, therefore, increases crack resistance and post-cracking behaviour of BFRC [158]. The multiscale mechanisms that have been in

effect governing hybrid RHA–Alccofine–basalt fiber systems are synthesized in Table 12, showing how complementary early-age hydration, long-term pozzolanic activity, ITZ refinement, and enhanced fiber-matrix bonding has a combined effect on strength, durability, and sustainability.

As a combination of the supplementary C–S–H formation of RHA and Alccofine is depicted in Figure 29, the densification of the ITZ, fiber anchorage, and retardation of fiber pull-out increase the load transfer and effective crack-bridging action.

Altogether, despite the fact that there are no direct experimental microstructural investigations of RHA–Alccofine–based BFRC, the combined data of closely related systems strongly imply that the combination of RHA and Alccofine leads to the densification of the matrix, refinement of the pores, and ITZ strengthening, which, in turn, enhances the mechanical performance and durability of basalt fiber reinforced concrete.

6.3 Practical Implications on Workability and Constructability

In addition to providing improved mechanical performance and durability, RHA–Alccofine-based BFRC may have its practical workability negatively influenced by the synergistic effect of SCMs and fibers.

The total surface area of Ultrafine Alccofine is high and therefore more water is demanded or more energy is required to mix to gain uniform dispersion [20, 122]. Equally, porous high-surface-area particles of RHA absorb mix water and may have decreased slump and flowability [24, 121]. The basalt fibers add mechanical interlocking and entanglement to these and further limit the flow and make the consistent distribution of the fibers in the matrix difficult [12, 16]. All these parameters could raise the mixing energy demands, cause higher

segregation or fiber balling, and adversely affect the simple placement, especially of high-fiber or low-slump mixtures. The water-binder ratio, the use of appropriate superplasticizers, proper management of mixing sequence and time is thus a very critical factor to ensure that the workability is high without reducing performance. Table 13 shows that Alccofine dominates the performance in young ages with accelerated hydration and rice husk ash controls the performance in old ages with long-term strength and durability with sustained pozzolanic reactions and that basalt fibers are the ones that offer complementary crack control at advanced ages.

7. Limitations of Current Literature and Research Gaps

Although a significant number of research works has been done on the implementation of RHA and Alccofine in fiber-reinforced concrete, there are actually several irregularities that must remain:

- **The lack of the ternary OPC-BFRC studies:** most of the studies focus on single SCM systems or binary ones; no systematically arranged tests on the OPC-with-RHA, Alccofine and basalt fiber are carried out.
- **In RHA quality variability:** The burning temperature, particle size and amorphous silica composition will exhibit a very significant level of variability that effects the pozzolanic reactivity in a material and causes mechanism and durability variation.

Table 13. Evolution of mechanical and durability performance of hybrid RHA–Alccofine concrete with curing age

Performance Aspect	Early Age (1–7 days)	Later Age (28 days and beyond)	Dominant SCM Contribution
Compressive strength	Rapid strength gain due to accelerated hydration and nucleation of C–S–H	Continued strength development from secondary C–S–H formation	Early: Alccofine Late: RHA
Tensile/flexural response	Improved fiber stress transfer due to denser early paste	Enhanced crack-bridging efficiency from refined matrix	Combined
Permeability / water absorption	Initial pore filling and reduced capillary connectivity	Progressive pore refinement and sealing of microcracks	Early: Alccofine Late: RHA
Chloride penetration resistance	Reduced early ingress from compact paste structure	Long-term diffusion resistance due to densified C–S–H network	Combined
Sulfate/chemical resistance	Lower availability of free $\text{Ca}(\text{OH})_2$	Formation of stable hydrates and reduced reactive phases	RHA-dominant
ITZ development (aggregate–paste–fiber)	Thinner ITZ from ultrafine particle packing	Stronger ITZ from continuous secondary hydration	Early: Alccofine Late: RHA
Fiber–matrix bonding	Improved early mechanical interlock	Enhanced chemical bonding and pull-out resistance	Combined

- **Sensitivity of Alccofine performance:** Sensitivity of very young hydration behaviour and strength gain is highly conditioned by fineness of the particles and curing behaviour conditions which are often reported and standardized inadequately.
- **Scale-up and field implementation risks:** the findings of laboratory scale are not likely to be applied directly in practice due to the workability, fiber scattering, and long-lasting contact with the environment issues.
- **Low-quantitative validation:** the gains in strength and permeability and durability are often required to be extrapolated of analogous systems and not directly determined in ternary OPC-BFRC mixtures.

Implications: These disadvantages are an argument of the need to perform experiments in a systematic manner, standardized characterization of SCMs, and a multi-scale performance measurement prior to performing it on a large scale. Analysis of these gaps has presented an articulate exposition of the direction the research will take in future as it is explained in the next section.

8. Future Research Directions

The following generation of a study should be in a position to carefully look into the practical application of the RHA-Alccofine based BFRC implementation through a combination of material development, durability tests as well as sustainability tests. Specific research directions which are testable are as follows:

8.1 Material Standardization and Characterization

- To find out the influence of RHA burning temperatures (650, 675, 700 °C) and particle sizes (<45 µm, <75 µm) and amorphous silica content (80–95%) to compressive strength and flexural strength at 7, 28, 90 days.
- Test variability Alccofine by testing the variability of the grades and particle sizes to ascertain their effects on the early age hydration dynamics and ITZ densification.
- Experiment Compare basalt fibers of diverse diameters, tensile strength and surface modification (e.g. coated, non-coated) to the efficiency of fiber- matrix bonding and crack-bridging behaviour.

8.2 Optimized Mix Design

- Test mixtures (ternary) of RHA (10%, 15%, 20%), Alccofine (8%, 10%, 12%) and basalt

fibers (0.1%, 0.25%, 0.5% by volume) so as to be able to decide the percentages to use in order to reach strength, durability and workability.

- Establish the effect of hydration behavior on the hydration behavior at early age and late age due to the ratio of water-binders (0.30-0.45).

8.3 Durability and Long-Term Performance

- Conduct a systematic study of the chloride, water-uptake, sulfate resistance, carbonation depth and micro-cracks development on the first ages (7–28 days old) and on the long ages (90–180 days old).
- Controlled laboratory and simulated field fatigue, freeze-thaw and self-healing test behaviour.

8.4 Micro structural and Mechanistic Insights

- Apply methods of high characterization such as nano indentation, 3D micro-CT and in situ SEM as a test of monitor the variation of hydration and creation of ITZ and contact of the fiber and the matrix over a period of time.
 - Include the outcomes of experimental studies on microstructure by integrating numerical modeling of the processes at the micromechanical level to identify mechanical performance and crack-propagation.
5. Sustainability and Work Practice
- Calculate life-cycle assessment (LCA) and cost-boundary analysis of decrease in CO₂ emissions and embodied energy and general cost.
 - Pilot scale tests in structural elements (e.g., bridge decks, marine elements, pavements) that are going to be subject to test in order to ascertain the working behaviour at pumping and placement, early cracking under field testing conditions.

In cases where the needs of a research are formulated as measurable experiments, then the subject matter can graduate to a mechanistic level of knowledge to established design recommendations. These studies will help in coming up with standardized, lasting and low carbon BFRC that can be used in the large scale of engineering requirements.

9. Conclusions

This is a critical analysis of the recent inventions with Basalt Fiber reinforced Concrete (BFRC) which involves using Rice Husk Ash (RHA) and Alccofine as

secondary cementitious materials (SCMs). The study was discussed according to mechanical performance, durability, microstructural properties, and the critical knowledge gaps and research needs that are required in the future:

- **Microstructure and hydration:** RHA + Alccofine also should lead to a high density of the microstructure in comparison to using each material separately. The hydration acceleration (alccofine), and long-term pozzolanic activity (RHA) are offered in the early age and long-term respectively.
- **Mechanical performance:** According to the tendencies of related systems, compressive and flexural strength can be improved by about 15–25% in comparison with conventional concrete at the optimal dosages (RHA 10–15%, Alccofine 8–12% by volume, basalt fibers 0.075–0.6%). Basalt fibers help in crack bridging, slower crack propagation and increased post peak ductility.
- **Durability:** RHA is expected to optimize the pore structure, and Alccofine can help decrease the level of calcium hydroxide. They might reduce permeability together and minimize the ingress of chlorides as well as enhance resistance to sulfate attack and carbonation.
- **Microstructural observation:** Literary SEM and XRD studies indicate that there are increased C-S-H gel formation and enhanced interfacial transition zone (ITZ). At 90 °C, basalt fibers are stable to chemical effects, and therefore, the integrity of interfaces can be preserved when subjected to heat.
- **Research gaps:** The vast majority of evidence is based on the short-term laboratory researches; there is a lack of field validation. There are no standardized methods of characterizing RHA and Alccofine, and there are few comprehensive life-cycle assessments. There is little development regarding quantitative correlations between microstructure development and performance and predictive models of the ternary system.

When experimental research validates these mechanistic examples on the RHA–Alccofine–BFRC ternary system, the hybrid concrete would potentially be a business viable, stable and sustainable material on the next generation infrastructure.

References

- [1] C.R. Gagg, Cement and concrete as an engineering material: An historic appraisal and case study analysis. *Engineering Failure Analysis*, 40, (2014) 114–140. <https://doi.org/10.1016/j.engfailanal.2014.02.004>
- [2] P. Monteiro, (2006). *Concrete: microstructure, properties, and materials*. McGraw-Hill Publishing.
- [3] R. Guo, J. Wang, L. Bing, D. Tong, P. Ciais, S.J. Davis, R.M. Andrew, F. Xi, Z. Liu, Global CO₂ uptake by cement from 1930 to 2019. *Earth System Science Data*, 13(4), (2021) 1791-1805. <https://doi.org/10.5194/essd-13-1791-2021>
- [4] A.M. Neville, (2011) *Properties of concrete*. Pitman Publishing.
- [5] R. Wang, Q. Zhang, Y. Li, Deterioration of concrete under the coupling effects of freeze–thaw cycles and other actions: A review. *Construction and Building Materials*, 319, (2001) 126045. <https://doi.org/10.1016/j.conbuildmat.2021.126045>
- [6] R. Wang, Z. Hu, Y. Li, K. Wang, H. Zhang, Review on the deterioration and approaches to enhance the durability of concrete in the freeze–thaw environment. *Construction and Building Materials*, 321, (2022) 126371. <https://doi.org/10.1016/j.conbuildmat.2022.126371>
- [7] A. Ahmed, Assessing the effects of supplementary cementitious materials on concrete properties: A Review. *Discover Civil Engineering*, 1(1), (2024). <https://doi.org/10.1007/s44290-024-00154-z>
- [8] J.T. da Silva Neto, P.R. Ribeiro Soares Junior, E.D. Reis, P. de Souza Maciel, P.C.C. Gomes, A. M.C. Gouveia, A.C. da Silva Bezerra, Fiber-reinforced cementitious composites: recent advances and future perspectives on key properties for high-performance design. *Discover Civil Engineering*, 2(1), (2025) 65. <https://doi.org/10.1007/s44290-025-00209-9>
- [9] K. Moolchandani, A. Sharma, K. Dharavath, Hybrid use of supplementary cementitious materials, industrial byproducts, and fillers for sustainable high-performance concrete. *Discover Civil Engineering*, 2(212), (2025). <https://doi.org/10.1007/s44290-025-00379-6>
- [10] A. Bentur, S. Mindess, (2006) *Fibre reinforced cementitious composites*. CRC Press, Routledge. <https://doi.org/10.1201/9781482267747>
- [11] V.C. Li, On Engineered cementitious composites (ECC). *Journal of Advanced Concrete Technology*, 1(3), (2003) 215–230. <https://doi.org/10.3151/jact.1.215>
- [12] J. Sim, C. Park, D. Y. Moon, Characteristics of basalt fiber as a strengthening material for concrete structures. *Composites Part B Engineering*, 36(6–7), (2005) 504–512. <https://doi.org/10.1016/j.compositesb.2005.02.002>
- [13] J. Branston, S. Das, S.Y. Kenno, C. Taylor,

- Mechanical behaviour of basalt fibre reinforced concrete. *Construction and Building Materials*, 124, (2016) 878–886. <https://doi.org/10.1016/j.conbuildmat.2016.08.009>
- [14] H. Liu, Y. Yu, Y. Liu, M. Zhang, L. Li, L. Ma, Y. Sun, W. Wang, A review on basalt fiber composites and their applications in clean energy sector and power grids. *Polymers*, 14(12), (2022) 2376. <https://doi.org/10.3390/polym14122376>
- [15] V.J. John, B. Dharmar, Influence of basalt fibers on the mechanical behavior of concrete—A review. *Structural Concrete*, 22(1), (2021) 491–502. <https://doi.org/10.1002/suco.201900086>
- [16] C. Jiang, K. Fan, F. Wu, D. Chen, Experimental study on the mechanical properties and microstructure of chopped basalt fibre reinforced concrete. *Materials & Design*, 58, (2014) 187–193. <https://doi.org/10.1016/j.matdes.2014.01.056>
- [17] Z. Xue, P. Qi, Z. Yan, Q. Pei, J. Zhong, Q. Zhan, Mechanical Properties and Crack Resistance of Basalt Fiber Self-Compacting High Strength Concrete: An Experimental Study. *Materials*, 16(12), (2023) 4374. <https://doi.org/10.3390/ma16124374>
- [18] M. Kosior-Kazberuk, J. Krassowska, Fracture toughness of concrete with basalt fiber. *MATEC Web of Conferences*, 265, (2019) 01008. <https://doi.org/10.1051/mateconf/201926501008>
- [19] S. Park, S. Wu, Z. Liu, S. Pyo, The role of Supplementary cementitious Materials (SCMs) in Ultra High Performance Concrete (UHPC): a review. *Materials*, 14(6), (2021) 1472. <https://doi.org/10.3390/ma14061472>
- [20] D. Ndahirwa, H. Zmamou, H. Lenormand, N. Leblanc, The role of supplementary cementitious materials in hydration, durability and shrinkage of cement-based materials, their environmental and economic benefits: A review. *Cleaner Materials*, 5, (2022) 100123. <https://doi.org/10.1016/j.clema.2022.100123>
- [21] M. Raghav, T. Park, H.M. Yang, S.Y. Lee, S. Karthick, H.S. Lee, Review of the effects of supplementary cementitious materials and chemical additives on the physical, mechanical and durability properties of hydraulic concrete. *Materials*, 14(23), (2021) 7270. <https://doi.org/10.3390/ma14237270>
- [22] L. Pang, Z. Liu, D. Wang, M. An, Review on the Application of Supplementary Cementitious Materials in Self-Compacting Concrete. *Crystals*, 12(2), (2022) 180. <https://doi.org/10.3390/cryst12020180>
- [23] T.A. Fode, Y.A.C. Jande, T. Kivevele, Effects of different supplementary cementitious materials on durability and mechanical properties of cement composite – Comprehensive review. *Heliyon*, 9(7), (2023) e17924. <https://doi.org/10.1016/j.heliyon.2023.e17924>
- [24] A. Siddika, Md. A.A. Mamun, R. Alyousef, H. Mohammadhosseini, State-of-the-art-review on rice husk ash: A supplementary cementitious material in concrete. *Journal of King Saud University - Engineering Sciences*, 33(5), (2020) 294–307. <https://doi.org/10.1016/j.jksues.2020.10.006>
- [25] X. Yin, M.M. Rahman, Y. Sun, Y. Zhao, J. Wang, Sustainable Soil–Cement Composites with Rice Husk Ash and Silica Fume: A Review of Performance and Environmental Benefits. *Materials*, 18(12), (2025) 2880. <https://doi.org/10.3390/ma18122880>
- [26] A.K. Rajak, D.L. Mahato, S. Dalal, S.F. Zeenath, A.H. Hirad, R. Pothu, M. Srinivaas, S. Nangan, R. Boddula, Development, assessment, and efficiency of rice husk ash (RHA) infused by eggshell as a hybrid catalyst towards biodiesel synthesis from iluppaiennai oil. *Biomass and Bioenergy*, 204, (2026) 108347. <https://doi.org/10.1016/j.biombioe.2025.108347>
- [27] P. Sohtun, D. Deb, N. Bora, R. Goswami, P.K. Choudhury, R. Boddula, P.K. Sarangi, R. Kataki, T.A. Kurniawan, Agriculture biomass-derived carbon materials for their application in sustainable energy storage. *Carbon Letters*, 35(2), (2025) 481-513. <https://doi.org/10.1007/s42823-025-00884-9>
- [28] M.C.G. Juenger, R. Siddique, Recent advances in understanding the role of supplementary cementitious materials in concrete. *Cement and Concrete Research*, 78 (2015) 71-80. <https://doi.org/10.1016/j.cemconres.2015.03.018>
- [29] X.Q. Wang, C.L. Chow, D. Lau, Multiscale perspectives for advancing sustainability in fiber reinforced ultra-high performance concrete. *Npj Materials Sustainability*, 2(1), (2024). <https://doi.org/10.1038/s44296-024-00021-z>
- [30] A. Abu Taqa, U.A. Ebead, M.O. Mohsen, M.O. Aburumman, A. Senouci, W. Maherzi, D. Qtiashat, Experimental Assessment of the Strength and Microstructural Properties of Fly Ash-Containing Basalt Fiber-Reinforced Self-Compacting Sustainable Concrete. *Journal of Composites Science*, 9(2), (2025) 79. <https://doi.org/10.3390/jcs9020079>
- [31] I.A. Ja'e, R.A.N. bin Raja Sazrin, A. Syamsir, N. Bheel, C.V. Amaechi, T.H. Min, V. Anggraini, Optimisation of mechanical properties and impact resistance of basalt fibre reinforced concrete containing silica fume: Experimental and response surface assessment. *Developments in the Built Environment*, 17, (2024) 100368. <https://doi.org/10.1016/j.dibe.2024.100368>
- [32] R. Siddique, K. Singh, P. Kunal, M. Singh, V. Corinaldesi, A. Rajor, Properties of bacterial rice

- husk ash concrete. *Construction and Building Materials*, 121, (2016) 112–119. <https://doi.org/10.1016/j.conbuildmat.2016.05.146>
- [33] B. Sagar, M.V.N. Sivakumar, Use of alccofine-1203 in concrete: review on mechanical and durability properties. *International Journal of Sustainable Engineering*, 14(6), (2021) 2060–2073. <https://doi.org/10.1080/19397038.2021.1970275>
- [34] J. Militký, R. Mishra, H. Jamshaid, (2018) Basalt fibers. *Handbook of Properties of Textile and Technical Fibres (Second Edition)*, 805-840. <https://doi.org/10.1016/B978-0-08-101272-7.00020-1>
- [35] V. Fiore, T. Scalici, G. Di Bella, A. Valenza, A review on basalt fibre and its composites. *Composites Part B Engineering*, 74, (2015) 74–94. <https://doi.org/10.1016/j.compositesb.2014.12.034>
- [36] B.N. Al-Kharabsheh, M.M. Arbili, A. Majdi, S.M. Alogla, A. Hakamy, J. Ahmad, A.F. Deifalla, Basalt fiber reinforced concrete: A compressive review on durability aspects. *Materials*, 16(1), (2023) 429. <https://doi.org/10.3390/ma16010429>
- [37] M.T. Elshazli, K. Ramirez, A. Ibrahim, M. Badran, Mechanical, durability and corrosion properties of basalt fiber concrete. *Fibers*, 10(2), (2022) 10. <https://doi.org/10.3390/fib10020010>
- [38] A.M. Tahwia, K.A. Helal, O. Youssf, Chopped Basalt Fiber-Reinforced High-Performance Concrete: An Experimental and Analytical study. *Journal of Composites Science*, 7(6), (2023) 250. <https://doi.org/10.3390/jcs7060250>
- [39] M. Khan, M. Cao, C. Xie, M. Ali, Efficiency of basalt fiber length and content on mechanical and microstructural properties of hybrid fiber concrete. *Fatigue & Fracture of Engineering Materials & Structures*, 44(8), (2021) 2135–2152. <https://doi.org/10.1111/ffe.13483>
- [40] J. Chen, J. Mu, A. Chen, Y. Long, Y. Zhang, J. Zou, Experimental study on the properties of Basalt Fiber–Cement-Stabilized Expansive soil. *Sustainability*, 16(17), (2024) 7579. <https://doi.org/10.3390/su16177579>
- [41] H. An, Y. Song, L. Liu, X. Meng, Experimental Study of the Compressive Strengths of Basalt Fiber-Reinforced Concrete after Various High-Temperature Treatments and Cooling in Open Air and Water. *Applied Sciences*, 11(18), (2021) 8729. <https://doi.org/10.3390/app11188729>
- [42] W.K.V.J.B. Kulasooriya, R.S.S. Ranasinghe, U.S. Perera, P. Thisovithan, I.U. Ekanayake, D.P.P. Meddage, Modeling strength characteristics of basalt fiber reinforced concrete using multiple explainable machine learning with a graphical user interface. *Scientific Reports*, 13(1), (2023) 13138. <https://doi.org/10.1038/s41598-023-40513-x>
- [43] X. Hong, Y. Song, J.C. Lee, Mechanical properties and microstructure of lightweight aggregate concrete incorporating basalt fiber. *Buildings*, 15(19), (2025) 3548. <https://doi.org/10.3390/buildings15193548>
- [44] J. Yong, H. Jichuan, L. Yonglin, J. Lujun, (2024) Performance Evaluation of Calcined Phosphogypsum Reinforced with Basalt Fiber and Calcium Carbonate Whiskers: A Study on Individual and Mixed Tests, *Preprints.org*. <https://doi.org/10.20944/preprints202402.1028.v1>
- [45] Z. He, X. Zhao, M. Ye, W. Zuo, X. Nie, J. Zhao, Study on the effect of basalt fiber content and length on mechanical properties and durability of coal gangue concrete. *Sustainability*, 16(21), (2024) 9310. <https://doi.org/10.3390/su16219310>
- [46] X. Wang, J. He, A.S. Mosallam, C. Li, H. Xin, The effects of fiber length and volume on material properties and crack resistance of basalt Fiber reinforced concrete (BFRC). *Advances in Materials Science and Engineering*, 2019(1), (2019) 1–17. <https://doi.org/10.1155/2019/7520549>
- [47] J. Johnson, E.S, S.R, Influence of hybrid basalt fibre with varied length on the mechanical properties of normal and high strength concrete. *Research on Engineering Structures and Materials*, 12(1), (2024) 679–696. <http://dx.doi.org/10.17515/resm2024.239me0413rs>
- [48] P. Smarzewski, A. Jancy, Comparative Study on Mechanical Performance and Toughness of High-Performance Self-Compacting Concrete with Polypropylene and Basalt Fibres. *Materials*, 18(16), (2025) 3833. <https://doi.org/10.3390/ma18163833>
- [49] M. Gupta, R. Raj, A.K. Sahu, Mechanical properties of high strength concrete incorporating chopped basalt fibers: experimental and analytical study. *Materials Research Express*, 9(12), (2022) 125305. <https://doi.org/10.1088/2053-1591/aca644>
- [50] Y. Shu, J. Zhang, Effect of basalt fiber content and length on the strength and crack development of polyvinyl Alcohol/Basalt hybrid Fiber-Reinforced cement soil. *Polymers*, 15(9), (2023) 2146. <https://doi.org/10.3390/polym15092146>
- [51] M. Sarmah, B. Roy, R.A. Mozumder, A.I. Laskar, Effect of chopped basalt fibers on the cyclic behavior of RCC Beam–Column subassemblies. *Arabian Journal for Science and Engineering*, 43(4), (2017) 1865–1874. <https://doi.org/10.1007/s13369-017-2801-y>
- [52] L. Lu, S. Wu, Y. Qin, G. Yuan, Q. Zhao, J.H. Doh,

- The Chloride Ion Penetration Mechanism in Basalt Fiber Reinforced Concrete under Compression after Elevated Temperatures. *Applied Sciences*, 11(21), (2021) 10137. <https://doi.org/10.3390/app112110137>
- [53] Y. Hu, Z. Wang, Z. Chen, C. Wang, S. Ding, Z. Nie, T. Hou, G. Zhao, The Improving Role of Basalt Fiber on the Sulfate–Chloride Multiple Induced Degradation of Cast-In-Situ Concrete. *Materials*, 17(18), (2024) 4454. <https://doi.org/10.3390/ma17184454>
- [54] Y. Luo, D. Niu, L. Su, Chloride Diffusion Property of Hybrid Basalt–Polypropylene Fibre-Reinforced Concrete in a Chloride–Sulphate Composite Environment under Drying–Wetting Cycles. *Materials*, 14(5), (2021) 1138. <https://doi.org/10.3390/ma14051138>
- [55] Q. Su, J. Xu, The Effect of Basalt Fiber on Concrete Performance under a Sulfate Attack Environment. *Journal of Renewable Materials*, 11(1), (2022) 233–244. <https://doi.org/10.32604/jrm.2023.020573>
- [56] M. Hanafi, E. Aydin, A. Ekinici, Engineering properties of basalt Fiber-Reinforced Bottom ash Cement paste composites. *Materials*, 13(8), (2020) 1952. <https://doi.org/10.3390/ma13081952>
- [57] H.V. Haran, J. Sandhiya, M. Ponraj, Strength and Durability Properties of Basalt Fiber Reinforced Concrete. *International Journal of Novel Research and Development*, 9(5), (2024) c425–c446.
- [58] Q. Su, J. Xu, (2022) Influence of Basalt/Polypropylene Fiber on Workability, Permeability and Uniaxial Compressive Properties of Rubber Concrete. SSRN. <https://dx.doi.org/10.2139/ssrn.4176011>
- [59] T.M. Borhan, Properties of glass concrete reinforced with short basalt fibre. *Materials and Design* 42, (2012) 265–271. <https://doi.org/10.1016/j.matdes.2012.05.062>
- [60] A.T. Shahid, M. Hofmann, M. Garrido, J.R. Correia, I.C. Rosa, Freeze–Thaw Durability of basalt fibre reinforced Bio-Based unsaturated polyester composite. *Materials*, 16(15) (2023) 5411. <https://doi.org/10.3390/ma16155411>
- [61] Y. Guo, J. Gao, J. Lv, Experimental study on the frost resistance of basalt fiber reinforced concrete. *Materials*, 17(18), (2024) 4593. <https://doi.org/10.3390/ma17184593>
- [62] X. Yuan, M. Dai, M. Li, F. Liu, Study of the Freeze–Thaw Resistance for Composite Fiber Recycled Concrete with Sulphate Attack Exposure. *Buildings*, 13(4), (2023) 1037. <https://doi.org/10.3390/buildings13041037>
- [63] W. Li, H. Liu, B. Zhu, X. Lyu, X. Gao, C. Liang, Mechanical properties and Freeze–Thaw durability of basalt fiber reactive powder concrete. *Applied Sciences*, 10(16), (2020) 5682. <https://doi.org/10.3390/app10165682>
- [64] M. Cerný, Z. Chlup, J. Kužma, M. Růžička, L. Ševčík, P. Kácha, J. Schweigstilllová, J. Svítlová, A. Strachota, Fire Safety and Impact and Frost Resistance of Basalt Fiber-Reinforced Polysiloxane Matrix Composite Processed under Partial Pyrolysis Conditions. *Journal of Composites Science*, 8(10), (2024) 405. <https://doi.org/10.3390/jcs8100405>
- [65] B. Wang, L. Xu, T. Chen, B. Hou, J. Liu, Y. Shen, R. Kuang, High-Temperature Mechanical Properties of Basalt Fibers: A Step Towards Fire-Safe Materials for Photovoltaic Applications. *Sustainability*, 16(24), (2024) 10853. <https://doi.org/10.3390/su162410853>
- [66] H. Zeng, J. Zhang, Y. Li, X. Su, C. Gu, K. Zhang, Mechanical properties and microstructure of basalt fiber reinforced concrete under the Single-Side Salt-Freezing–Drying–Wetting cycles. *International Journal of Concrete Structures and Materials*, 16(1), (2022). <https://doi.org/10.1186/s40069-022-00535-7>
- [67] H. M. Hamada, F. Abed, Z. A. Al-Sadoon, A. Hassan, Enhancing Concrete Strength and Microstructure with Basalt and Steel Fibers in Acid and Base Environments Incorporating Desert Sand. *International Journal of Concrete Structures and Materials*, 19(1), (2025). <https://doi.org/10.1186/s40069-024-00741-5>
- [68] Y. Gong, Q. Hua, Z. Wu, Y. Yu, A. Kang, X. Chen, H. Dong, Effect of basalt/steel individual and hybrid fiber on mechanical properties and microstructure of UHPC. *Materials*, 17(13), (2024) 3299. <https://doi.org/10.3390/ma17133299>
- [69] J.V. Jenifer, D. Brindha, Development of hybrid steel-basalt fiber reinforced concrete - in aspects of flexure, fracture and microstructure. *Revista de la Construcción*, 20(1), (2021) 62–90. <https://doi.org/10.7764/RDLC.20.1.62>
- [70] A.J. Sudhakar, B. Muthusubramanian, Development of Basalt Fiber Reinforced Fine-Grained Cementitious Composites for Textile Reinforcements. *Journal of Composites Science*, 6(12), (2022) 396. <https://doi.org/10.3390/jcs6120396>
- [71] D. Wang, Y. Wu, Z. Xu, N. Xu, C. Li, X. Tian, F. Shi, H. Wang, Effect of Basalt Fibers on the Performance of CO₂-Cured Recycled Aggregate Concrete Composite Slab–Column Assemblies with Bolted Connections Under NaCl Erosion. *Coatings*, 15(9), (2025) 1053. <https://doi.org/10.3390/coatings15091053>
- [72] M. Amran, R. Fediuk, S. Klyuev, D.N. Qader, Sustainable development of basalt fiber-reinforced high-strength eco-friendly concrete with a modified composite binder. *Case Studies in Construction Materials*, 17, (2022) e01550.

- <https://doi.org/10.1016/j.cscm.2022.e01550>
- [73] M. Khan, J. Lao, M.R. Ahmad, J.G. Dai, Influence of high temperatures on the mechanical and microstructural properties of hybrid steel-basalt fibers based ultra-high-performance concrete (UHPC). *Construction and Building Materials*, 411, (2023) 134387. <https://doi.org/10.1016/j.conbuildmat.2023.134387>
- [74] V. Malagavelli, S. Angadi, J.S.R. Prasad, S.Joshi, Influence of metakaolin in concrete as partial replacement of cement. *International Journal of Civil Engineering and Technology (IJCIET)* 9(7), (2018) 105-111.
- [75] D. Pedro, J. De Brito, L. Evangelista, Evaluation of high-performance concrete with recycled aggregates: Use of densified silica fume as cement replacement. *Construction and Building Materials*, 147, (2017) 803–814. <https://doi.org/10.1016/j.conbuildmat.2017.05.007>
- [76] B. Singh, (2018) Rice husk ash. *Waste and Supplementary Cementitious Materials in Concrete*, 417-460. <https://doi.org/10.1016/B978-0-08-102156-9.00013-4>
- [77] J. Sam, Compressive Strength of Concrete using Fly Ash and Rice Husk Ash: A Review. *Civil Engineering Journal*, 6(7), (2020) 1400–1410. <https://doi.org/10.28991/cej-2020-03091556>
- [78] J. Ahmad, K.J. Kontoleon, A. Majdi, M. T. Naqash, A.F. Deifalla, N. Ben Kahla, H.F. Isleem, S.M. Qaidi, (2022). A comprehensive review on the ground granulated blast furnace slag (GGBS) in concrete production. *Sustainability*, 14(14), 8783. <https://doi.org/10.3390/su14148783>
- [79] X. Li, Y. Ma, X. Shen, Y. Zhong, Y. Li, Study of Hydration and Microstructure of Mortar Containing Coral Sand Powder Blended with SCMs. *Materials*, 13(19), (2020) 4248. <https://doi.org/10.3390/ma13194248>
- [80] N. Shafiq, M.F. Nuruddin, A.E.A. Elshekh, A.F.M. Salihi, Effect of chopped basalt fiber on the fresh and hardened properties of fly ash high strength concrete. *Applied Mechanics and Materials*, 567, (2014) 381–386. <https://doi.org/10.4028/www.scientific.net/AMM.567.381>
- [81] Y. Sun, H. Jia, J. Wang, Y. Ding, Y. Guan, D. Lei, Y. Li, Calculation model for the degree of hydration and strength prediction in Basalt fiber-reinforced lightweight aggregate concrete. *Buildings*, 15(15), (2025) 2699. <https://doi.org/10.3390/buildings15152699>
- [82] B.L.N.S. Srinath, C.K. Patnaikuni, K.V.G.D. Balaji, B.S. Kumar, M. Manjunatha, A prospective review of alccofine as supplementary cementitious material. *Materials Today Proceedings*, 47, (2021)3953–3959. <https://doi.org/10.1016/j.matpr.2021.03.719>
- [83] P. Kumar, A. Gogineni, R. Upadhyay, Mechanical performance of fiber-reinforced concrete incorporating rice husk ash and recycled aggregates. *Journal of Building Pathology and Rehabilitation*, 9(2), (2024). <https://doi.org/10.1007/s41024-024-00500-9>
- [84] B. Sagar, M.V.N. Sivakumar, Study on Basalt Fiber Reinforced Concrete: Mechanical and microstructural properties and analytical modelling of compressive Stress-Strain curves. *European Journal of Environmental and Civil Engineering*, 27(5), (2022) 2088–2115. <https://doi.org/10.1080/19648189.2022.2110161>
- [85] B. Mobasher, (2011) *Mechanics of fiber and textile reinforced cement composites*. CRC press. <https://doi.org/10.1201/b11181>
- [86] S. Barbhuiya, B.B. Das, D. Adak, A. Rajput, V. Katare, Rice husk ash in structural concrete: influence on strength, durability and sustainability. *Discover Concrete and Cement*, 1(1), (2025). <https://doi.org/10.1007/s44416-025-00013-9>
- [87] E.E. Ambrose, O.R. Ogirigbo, T.B. Bello, S. U. Akpando, Compressive Strength, Density, and Setting Time of Concrete Blended with Rice Husk Ash. *Engineering Proceedings*, 124(1), (2026) 1. <https://doi.org/10.3390/engproc2026124001>
- [88] E. Khankhaje, H. Jang, J. Kim, M. Rafieizonooz, Utilizing rice husk ash as cement replacement in pervious concrete: A review. *Developments in the Built Environment*, 22, (2025) 100675. <https://doi.org/10.1016/j.dibe.2025.100675>
- [89] K. Ganesan, K. Rajagopal, K. Thangavel, Rice husk ash blended cement: Assessment of optimal level of replacement for strength and permeability properties of concrete. *Construction and Building Materials*, 22(8), (2007) 1675–1683. <https://doi.org/10.1016/j.conbuildmat.2007.06.011>
- [90] H. Chao-Lung, B. L. Anh-Tuan, C. Chun-Tsun, Effect of rice husk ash on the strength and durability characteristics of concrete. *Construction and Building Materials*, 25(9), (2011) 3768–3772. <https://doi.org/10.1016/j.conbuildmat.2011.04.009>
- [91] M.H. Zhang, V.M. Malhotra, High-Performance concrete incorporating rice husk ash as a supplementary cementing material. *ACI Materials Journal*, 93(6), (1996) 629-636. <https://doi.org/10.14359/9870>
- [92] M.A. Albadrani, Strength Development of PPC Concrete with Rice Husk Ash: Optimal Replacement Levels for Sustainable Construction. *Sustainability*, 17(18), (2025) 8258. <https://doi.org/10.3390/su17188258>

- [93] D.O. Nduka, B.J. Olawuyi, E.O. Fagbenle, B.G. Fonteboa, Mechanical and microstructural properties of high-performance concrete made with rice husk ash internally cured with superabsorbent polymers. *Heliyon*, 8(9), (2022) e10502. <https://doi.org/10.1016/j.heliyon.2022.e10502>
- [94] M.F. Ullah, H. Tang, A. Ullah, K. Khan, Synergistic effects of rice husk ash and extracted microsilica on the performance of high-strength concrete. *Scientific Reports*, 15(1), (2025) 41274. <https://doi.org/10.1038/s41598-025-25218-7>
- [95] R. Madandoust, M.M. Ranjbar, H.A. Moghadam, S.Y. Mousavi, Mechanical properties and durability assessment of rice husk ash concrete. *Biosystems Engineering*, 110(2), (2011) 144–152. <https://doi.org/10.1016/j.biosystemseng.2011.07.009>
- [96] O. Zaid, J. Ahmad, M.S. Siddique, F. Aslam, Effect of incorporation of rice husk ash instead of cement on the performance of steel fibers reinforced concrete. *Frontiers in Materials*, 8, (2021). <https://doi.org/10.3389/fmats.2021.665625>
- [97] M.M. Meraz, N.J. Mim, M.T. Mehedi, E.N. Farsangi, S.A.K. Arafin, R.K. Shrestha, M.S. Hussain, On the utilization of rice husk ash in high-performance fiber reinforced concrete (HPFRC) to reduce silica fume content. *Construction and Building Materials*, 369, (2023) 130576. <https://doi.org/10.1016/j.conbuildmat.2023.130576>
- [98] D.H. Vo, M.H. Nguyen, M.H. Nguyen, C.L. Hwang, T.P. Huynh, Influence of rice husk ash and hybrid fiber on engineering properties of densified high-performance fiber-reinforced concrete. *Proceedings of the Institution of Mechanical Engineers Part L Journal of Materials Design and Applications*, 237(11), (2023) 2445–2457. <https://doi.org/10.1177/14644207231180292>
- [99] M.J. Memon, A.A. Jhatial, A. Murtaza, M.S. Raza, K.B. Phulpoto, Production of eco-friendly concrete incorporating rice husk ash and polypropylene fibres. *Environmental Science and Pollution Research*, 28(29), (2021) 39168–39184. <https://doi.org/10.1007/s11356-021-13418-3>
- [100] S. Azhagarsamy, K. Jaiganesan, A study on strength properties of concrete with rice husk ash and silica fume with addition of glass fiber. *International Research Journal of Engineering and Technology*, 3(8), (2016) 1681-1684.
- [101] M.M. Meraz, M.H.R. Sobuz, N.J. Mim, A. Ali, M.S. Islam, M.A. Safayet, M.T. Mehedi. Using rice husk ash to imitate the properties of silica fume in high-performance fiber-reinforced concrete (HPFRC): A comprehensive durability and life-cycle evaluation. *Journal of Building Engineering*, 76, (2023) 107219. <https://doi.org/10.1016/j.jobe.2023.107219>
- [102] A.M. Mohamed, B.A. Tayeh, S.S. Majeed, Y.I.A. Aisheh, M.A.B.M. Ariffin, Optimizing rice husk ash for ultra-high-performance concrete: a comprehensive review of mechanical properties, durability, and environmental benefits, *Reviews on Advanced Materials Science*, 64(1), (2025). <https://doi.org/10.1515/rams-2025-0146>
- [103] Z. Rong, J. Ding, Z. Cui, W. Sun, Mechanical properties and microstructure of ultra-high performance cement-based composite incorporating RHA. *Advances in Cement Research*, 31(10), (2018) 472–480. <https://doi.org/10.1680/jadcr.17.00209>
- [104] P. Maleki, M. Shadabfar, H. Kordestani, An experimental investigation of the effects of adding polymer and basalt fibers on the mechanical properties and durability of lightweight concrete. *Buildings*, 15(6), (2025) 911. <https://doi.org/10.3390/buildings15060911>
- [105] K. Sathvika, Sustainable concrete mixes using alccofine and waste materials. *International Journal of Emerging Research in Science Engineering and Management*, 1(1), (2025) 22–28. <https://doi.org/10.58482/ijersem.v1i1.4>
- [106] G.T. Kumaar, S. Gunasekar, N. Ramesh, (2023) Impact of Alccofine on the strength and durability properties of concrete. *Materials Today Proceedings*. <https://doi.org/10.1016/j.matpr.2023.11.036>
- [107] B. Sagar, S. MVN, Mechanical and microstructure characterization of alccofine based high strength concrete. *Silicon*, 14(3), (2021) 795–813. <https://doi.org/10.1007/s12633-020-00863-x>
- [108] S.C. Boobalan, V.A. Srivatsav, A.M.T. Nisath, A.P. Babu, V. Gayathri, A comprehensive review on strength properties for making Alccofine based high performance concrete. *Materials Today Proceedings*, 45, (2021) 4810–4812. <https://doi.org/10.1016/j.matpr.2021.01.278>
- [109] B. Baby, J. Anto, B. Johny, S.S. Rheology, strength and durability Characteristics of Alccofine Blended fibre reinforced self-consolidating concrete. *International Journal of Engineering & Technology*, 7(3.12), (2018) 209. <https://doi.org/10.14419/ijet.v7i3.12.16026>
- [110] S.S. Vivek, B. Karthikeyan, A. Bahrami, S.K. Selvaraj, R. Rajasakthivel, M. Azab, Impact and durability properties of alccofine-based hybrid fibre-reinforced self-compacting concrete. *Case Studies in Construction Materials*, 19, (2023) e02275. <https://doi.org/10.1016/j.cscm.2023.e02275>
- [111] B. Sankar, P. Ramadoss, Experimental and

- statistical investigations on alccofine based ternary blended high-performance concrete. *International Journal of Engineering*, 35(8), (2022) 1629–1640. <https://doi.org/10.5829/ije.2022.35.08b.19>
- [112] K. Rajanikara Swamy, K. Samatha, and A. Professor, (2022) Usage of Alccofine And Basalt Fiber on M60 Grade Concrete, 21. <http://materialsciencetech.com/mst/>
- [113] K. Ganesan, K. Rajagopal, K. Thangavel, Rice husk ash blended cement: Assessment of optimal level of replacement for strength and permeability properties of concrete. *Construction and Building Materials*, 22(8), (2007) 1675–1683. <https://doi.org/10.1016/j.conbuildmat.2007.06.011>
- [114] R. Siddique, (2008). Rice husk ash. In *Waste materials and by-products in concrete*, Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-74294-4_7
- [115] S. Lakshmikanth, M.C. Nataraja, Supreeth, Performance of High-Strength Concrete using Alccofine and GGBFS. *Journal of the Institution of Engineers (India) Series A*, 103(2), (2022) 567–580. <https://doi.org/10.1007/s40030-022-00635-3>
- [116] H. Zhou, B. Jia, H. Huang, Y. Mou, Experimental study on basic mechanical properties of basalt fiber reinforced concrete. *Materials*, 13(6), (2020) 1362. <https://doi.org/10.3390/ma13061362>
- [117] R. Balamuralikrishnan, J. Saravanan, Effect of addition of alccofine on the compressive strength of cement mortar cubes. *Emerging Science Journal*, 5(2), (2021) 155-170. <https://doi.org/10.28991/esj-2021-01265>
- [118] H.N. Rajakumara, M. Pradeep, Production of high strength Eco-Concrete incorporating alccofine and basalt fiber. *Recent Advances in Civil Engineering*. CTCS 2021. Lecture Notes in Civil Engineering. Springer, Singapore. https://doi.org/10.1007/978-981-19-1862-9_40
- [119] G. Kaplan, M.A.S. Elmekahal, Microstructure and durability properties of lightweight and high-performance sustainable cement-based composites with rice husk ash. *Environmental Science and Pollution Research*, 28, (2021) 52936–52962. <https://doi.org/10.1007/s11356-021-14489-y>
- [120] M. Mohsan UI Haque, M. Mudabir UI Haque, Improving Strength of Concrete using Alccofine and Rice Husk Ash. 12(4), (2025) 188-192.
- [121] S.A. Endale, W.Z. Taffese, D.H. Vo, M.D. Yehualaw, Rice husk ash in concrete. *Sustainability*, 15(1), (2022) 137. <https://doi.org/10.3390/su15010137>
- [122] C. Prithiviraj, J. Saravanan, D.R. Kumar, G. Murali, N. I. Vatin, P. Swaminathan, Assessment of Strength and Durability Properties of Self-Compacting Concrete Comprising Alccofine. *Sustainability (Switzerland)*, 14(10), (2022) 5895. <https://doi.org/10.3390/su14105895>
- [123] H.S. Gökçe, D. Hatungimana, K. Ramyar, Effect of fly ash and silica fume on hardened properties of foam concrete. *Construction and Building Materials*, 194, (2019) 1–11. <https://doi.org/10.1016/j.conbuildmat.2018.11.036>
- [124] A. Mohan, K. M. Mini, Strength studies of SCC incorporating silica fume and ultra fine GGBS. *Materials Today Proceedings*, 5(11), (2018) 23752–23758. <https://doi.org/10.1016/j.matpr.2018.10.166>
- [125] M. Amin, Properties of reactive powder concrete incorporating silica fume and rice husk ash. *Challenge Journal of Concrete Research Letters*, 9(4), (2018) 114. <https://doi.org/10.20528/cjcr.2018.04.003>
- [126] A. Ahmed, S. Ameer, S. Abbas, W. Abbass, A. Razzaq, A.M. Mohamed, A. Mohamed, Effectiveness of ternary blend incorporating rice husk ash, silica fume, and cement in preparing ASR resilient concrete. *Materials*, 15(6), (2022) 2125. <https://doi.org/10.3390/ma15062125>
- [127] M. Mathur, A. Mathur, Performance of Concrete by Partial Replacement of Alccofine -1203. *International Journal of Engineering Research & Technology*, 6(11), (2018) 1-5.
- [128] R.M. Andrew, Global CO₂ Emissions from Cement Production, 1928–2018. *Earth System Science Data*, 11(4), (2019) 1675-1710. <https://doi.org/10.5194/essd-11-1675-2019>
- [129] A.O. Pehlivan, Effect of Nanosilica Addition on the Mechanical Properties of Cement Mortars with Basalt Fibers with or without Silica Fume. *Journal of Sustainable Construction Materials and Technologies*, 7(1), (2022) 17–23. <https://doi.org/10.14744/jscmt.2022.09>
- [130] H. Lou, C. Ma, Q. Hong, (2024). Influence of Fly Ash and Basalt Fibers on the Properties of Recycled Pervious Concrete. in *Lecture Notes in Civil Engineering*, Springer, Singapore, 603, 62-75. https://doi.org/10.1007/978-981-97-5814-2_6
- [131] A.S. Kumar, C.K. Patnaikuni, B.S. Kumar, A Review of Alccofine and Steel Fiber Effects on Strength and Durability of Binary Concrete Mixes. *Innovative Infrastructure Solutions*, 10(7), (2025), <https://doi.org/10.1007/s41062-025-02093-9>
- [132] J. Liu, G. Guo, X. Wang, C. Lv, D. Wang, H. Geng, Investigation of Mechanical Properties of Recycled Aggregate Concrete Incorporating Basalt Fiber, Copper Slag, and Ground Granulated Blast Furnace Slag. *Buildings*, 15(13), (2025) 2214, <https://doi.org/10.3390/buildings15132214>
- [133] S.S. Charan, C.L.K. Murthy Gupta, A Comparative Study on Mechanical Properties of

- Basalt Fiber Reinforced Concrete with Partial Replacement of Cement with GGBS. *International Journal of Engineering Research & Technology*, 5(6), (2016) 62-67.
- [134] C. Girgin, Effect of Slag, Nano Clay and Metakaolin on Mechanical Performance of Basalt Fibre Cementitious Composites. *Construction and Building Materials*, 192, (2018) 70–84, <https://doi.org/10.1016/j.conbuildmat.2018.10.090>
- [135] K. Huang, Q. Ma, D. Ma, Effect of Basalt Fiber on Static and Dynamic Mechanical Properties of Metakaolin-Based Cement Clay. *Advances in Civil Engineering*, 2020(1), (2020), 1359163. <https://doi.org/10.1155/2020/1359163>
- [136] W. Xu, T. Y. Lo, W. Wang, D. Ouyang, P. Wang, F. Xing, Pozzolan Reactivity of Silica Fume and Ground Rice Husk Ash as Reactive Silica in a Cementitious System: A Comparative Study. *Materials*, 9(3), (2016), 146. <https://doi.org/10.3390/ma9030146>
- [137] A. Abolhasani, B. Samali, F. Aslani, Rice Husk Ash Incorporation in Calcium Aluminate Cement Concrete: Life Cycle Assessment, Hydration and Strength Development. *Sustainability*, 14(2), (2022) 1012. <https://doi.org/10.3390/su14021012>
- [138] P. Kumari, G. Kuma, Development of Ultra-High-Performance Concrete Using GGBS and Alccofine *International Journal for Research in Applied Science and Engineering Technology*, 12(7), (2024) 1010–1014. <https://doi.org/10.22214/ijraset.2024.63704>
- [139] D.O. Nduka, B.J. Olawuyi, O.I. Fagbenle, B.G. Fonteboa, Assessment of the Durability Dynamics of High-Performance Concrete Blended with a Fibrous Rice Husk Ash. *Crystals (Basel)*, 12(1), (2022), 75. <https://doi.org/10.3390/cryst12010075>
- [140] K. Meenatchi, K. Suguna, P.N. Raghunath, Performance Evaluation of Fibre Reinforced Concrete Containing Alccofine and Zeolite. *Indian Journal of Science and Technology*, 16(17), (2023) 1309–1322, <https://doi.org/10.17485/IJST/v16i17.2346>
- [141] L.M. Ordonez, J. Paya, A.M. Coats, F.P. Glasser, Reaction of rice husk ash with OPC and portlandite. *Advances in Cement Research*, 14(3), (2002) 113–119, <https://doi.org/10.1680/adcr.2002.14.3.113>
- [142] B. Suresh, P. R. K. Rajkumar, Studies on the Concrete with Composite Cement and Alccofine: from use of OPC Towards Low-Carbon Quaternary Binder. *Innovative Infrastructure Solutions*, 9(5), (2024) 129. <https://doi.org/10.1007/s41062-024-01432-6>
- [143] B. Akturk, Fracture Behavior of Alkali-Activated Basalt Powder/Slag Systems Reinforced with Basalt and Hybrid Fibers. *Materials and Structures*, 56(2), (2023) 46. <https://doi.org/10.1617/s11527-023-02139-3>
- [144] S. Quazi, S. Sonukumar, and K. Dabhade, Effect of basalt fiber and RHA on strength of Concrete-A Review, *International Journal of Engineering Research & Technology*, 5(3), (2016), 851-856.
- [145] H.K. Venkatanarayanan, P.R. Rangaraju, Evaluation of Sulfate Resistance of Portland cement Mortars Containing Low-Carbon Rice Husk Ash. *Journal of Materials in Civil Engineering*, 26(4), (2013) 582–592, [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000868](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000868)
- [146] K.M.A. Hossain, M.S. Anwar, Performance of Rice Husk Ash Blended Cement Concretes Subjected to Sulfate Environment. *Magazine of Concrete Research*, 66(24), (2014) 1237–1249, <https://doi.org/10.1680/macr.14.00108>
- [147] K.N. Kumar, R. Divahar, S.P. Sangeetha, R. Singh, M. Akash, Enhancing Alkaline Resistance of Concrete using Alccofine and Metakaolin in Mineral Admixtures of Sustainable Development. *European Journal of Environmental and Civil Engineering*, 28(16), (2024) 3749–3769, <http://dx.doi.org/10.1080/19648189.2024.2357676>
- [148] A.S. Kumar, C.K. Patnaikuni, B.S. Kumar, A review of Alccofine and Steel Fiber Effects on Strength and Durability of Binary Concrete Mixes. *Innovative Infrastructure Solutions*, 10(7), (2025). <https://doi.org/10.1007/s41062-025-02093-9>
- [149] N. Nisar, J.A. Bhat, Experimental Investigation of Rice Husk Ash on Compressive Strength, Carbonation and Corrosion Resistance of Reinforced Concrete. *Australian Journal of Civil Engineering*, 19(2), (2020) 155–163. <https://doi.org/10.1080/14488353.2020.1838419>
- [150] H. Sharma, D.K. Ashish, S.K. Sharma, Development of Low-Carbon Recycled Aggregate Concrete using Carbonation Treatment and Alccofine. *Energy Ecology and Environment*, 9(3), (2023) 230–240, <https://doi.org/10.1007/s40974-023-00299-0>
- [151] Z. Ma, H. Huang, X. Hu, H. Yang, Experiment Study on the Mechanical Properties and Alkali Silica Reaction (ASR) of Mortar Blended Rice Husk Ash (RHA). *Case Studies in Construction Materials*, 18, (2023) e02028. <https://doi.org/10.1016/j.cscm.2023.e02028>
- [152] P. R. Rao, R. Harika, G. K. George, K. Ravichandra, (2025). Influence of Metakaolin and Alccofine on the Fresh, Hardened, and Durability Properties of Blended Concrete: A Comprehensive Review. In *Lecture Notes in Civil Engineering*, Springer, Singapore, 737, 359–374. https://doi.org/10.1007/978-981-95-1491-5_28
- [153] N.M.S. Hasan, M.H.R. Sobuz, M.M.H. Khan, N.J. Mim, M.M. Meraz, S.D. Datta, M.J. Rana, A. Saha, A.S.M. Akid, M.T. Mehedi, M. Houda,

- Integration of Rice Husk Ash as Supplementary Cementitious Material in the Production of Sustainable High-Strength Concrete. *Materials*, 15(22), (2022) 8171. <https://doi.org/10.3390/ma15228171>
- [154] S.A. Mostafa, A.S. Faried, A.A. Farghali, M.M. El-Deeb, T.A. Tawfik, S. Majer, M. Abd Elrahman, Influence of Nanoparticles from Waste Materials on Mechanical Properties, Durability and Microstructure of UHPC. *Materials*, 13(20), (2020) 4530, <https://doi.org/10.3390/ma13204530>
- [155] D. Suriya, S.P. Chandar, P.T. Ravichandran, Impact of M-Sand on Rheological, Mechanical, and Microstructural Properties of Self-Compacting Concrete. *Buildings*, 13(5), (2023) 1126, <https://doi.org/10.3390/buildings13051126>
- [156] R. Liu, S. Zhao, S. Sun, Y. Cui, Experimental Study of the Mechanical Properties and Microstructure of Basalt Fiber-Reinforced Concrete. *Journal of Materials in Civil Engineering*, 35(7), (2023), 04023205. <https://doi.org/10.1061/JMCEE7.MTENG-14646>
- [157] D.D. Bui, J. Hu, P. Stroeven, Particle Size Effect on the Strength of Rice Husk Ash Blended Gap-Graded Portland Cement Concrete. *Cement and Concrete Composites*, 27(3), (2004) 357–366. <https://doi.org/10.1016/j.cemconcomp.2004.05.002>
- [158] M. Liu, W. Dai, C. Zhong, and X. Yang, Study on Mechanical Properties and Microstructure of Basalt Fiber Reactive Powder Concrete. *Buildings*, 12(10), (2022) 1734. <https://doi.org/10.3390/buildings12101734>
- [159] S.S.A.B. Padavala, V. Noolu, Y. Paluri, S.K.R. Bijiivemula, and U.K. Akula, A study on the Synthesis and Performance Evaluation of Fly Ash and Alccofine as Sustainable Cementitious Materials. *Scientific Reports*, 14(1), (2024) 19115. <https://doi.org/10.1038/s41598-024-67519-3>
- [160] D. Chopra, R. Siddique, Kunal, Strength, Permeability and Microstructure of Self-Compacting Concrete Containing Rice Husk Ash. *Biosystems Engineering*, 130, (2015) 72–80. <https://doi.org/10.1016/j.biosystemseng.2014.12.005>
- [161] R. Prasad, M. Pandey, Rice Husk Ash as a Renewable Source for the Production of ValueAdded Silica Gel and its Application: An Overview. *Bulletin of Chemical Reaction Engineering and Catalysis*, 7(1), (2012) 1–25. <https://doi.org/10.9767/bcrec.7.1.1216.1-25>
- [162] D.S. Jayanti, J. Mirza, R.P. Jaya, B.H.A. Bakar, N.A. Hassan, M.R. Hainin, Chloride Penetration of RHA Concrete under Marine Environment. *Proceedings of the Institution of Civil Engineers - Maritime Engineering*, 169(2), (2016) 76–85 <https://doi.org/10.1680/jmaen.2015.8>
- [163] Z. Li, J. Ma, H. Ma, X. Xu, (2018). Properties and Applications of Basalt Fiber and its Composites. in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 186(2) 012052. <https://doi.org/10.1088/1755-1315/186/2/012052>

Authors Contribution Statement

Sahil Samanta: Conceptualization, Methodology, Experimental Investigation, Data Curation, Formal Analysis, Writing-Original Draft. N. Lingeshwaran: Supervision, Validation, Writing-Review & Editing, Project Administration. All the authors have read and agreed to the published version of the manuscript.

Funding

The authors declare that no funds, grants or any other support were received during the preparation of this manuscript.

Competing Interests

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Has this article screened for similarity?

Yes

About the License

© The Author(s) 2026. The text of this article is open access and licensed under a Creative Commons Attribution 4.0 International License.