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RESEARCH ARTICLE

Comparative Study on the Performance of GGBS, UGGBS, and RHA-Incorporated Cement Mortar Mixes

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ABSTRACT

The environmental footprint of cement production has accelerated the pursuit of sustainable alternatives in the construction industry. Supplementary cementitious materials (SCMs), particularly those derived from industrial and agricultural waste, offer a promising approach to reducing cement consumption while maintaining performance. This study evaluates the fresh and mechanical behavior of binary, ternary, and quaternary cementitious mortar blends incorporating ground granulated blast-furnace slag (GGBS), ultrafine GGBS (UGGBS), and rice husk ash (RHA) as partial replacements for cement. A total of 32 mortar mixes were designed with water-to-binder (w/b) ratios ranging from 0.3 to 0.5 and varied replacement levels of RHA (0–20%), GGBS (0–25%), and UGGBS (10%). Flowability, compressive strength, and flexural strength were assessed to understand material interactions and optimize blend performance. Results indicate that RHA incorporation reduced workability due to its high surface area and porous nature; however, the inclusion of finer UGGBS significantly improved flow. The blend of GGBS and UGGBS demonstrated superior mechanical performance, while the UGGBS-RHA combination enhanced flexural strength compared to ternary mixes. The findings underscore the importance of particle fineness and material compatibility in multi-component binder systems. This study supports the integration of industrial by-products and agro-waste into cementitious matrices, promoting both environmental and performance benefits. Future research should focus on microstructural analysis, durability characteristics under aggressive exposure conditions, and the practical application of these blends in real-world construction scenarios.

Keywords: Supplementary cementitious materials, GGBS, Ultrafine GGBS, Rice husk ash, Sustainable mortars, Flowability, Strength, Sustainability

1. Introduction

The global surge in infrastructure and building development, particularly within emerging economies [1], is profoundly reshaping the world to support economic growth for an increasingly large population. However, this rapid expansion carries a substantial environmental burden. The construction and building sector is a significant contributor to global carbon emissions, accounting for nearly 40% of the world-wide total, releasing approximately 15 gigatonnes of carbon dioxide (CO₂) annually [2]. Within this, the

cement industry alone is responsible for roughly 7% of global CO₂ emissions, making it a critical focus for industrial greenhouse gas reduction efforts [3].

Sustainable construction aims to minimize the depletion of natural resources, reduce greenhouse gas emissions, and promote the well-being of both occupants and the surrounding community. Beyond the immediate environmental advantages, adopting sustainable construction practices offers substantial long-term economic benefits, including reduced operational costs, and an increased lifespan for structures. A key strategy to mitigate the environmental impact

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of cement production is the increased utilization of supplementary cementitious materials (SCMs). These materials, such as fly ash and ground granulated blast-furnace slag, possess inherent cementitious properties. Incorporating SCMs into concrete mixes significantly reduces the demand for clinker, the most energy-intensive component of cement, resulting in lower overall CO₂ emissions. Furthermore, the use of SCMs is widely recognized for enhancing the durability and long-term performance of cementitious systems, contributing to more sustainable and resilient infrastructure. The adoption of SCMs is projected to increase substantially in key emerging markets, including China, India, and Indonesia, aligning with global efforts to decarbonize the construction sector and adhere to evolving building material standards [4].

1.1. Industrial byproducts as supplementary cementitious materials (SCMs)

Industries generate many waste materials, including hazardous and non-hazardous substances. Effective management of industrial waste involves minimizing waste generation, recycling byproducts, and treating hazardous waste to prevent environmental contamination. One promising approach is the utilization of industrial byproducts in construction applications [5]. For example, slag, a derivative of steel production, is used as a partial substitute for cement in concrete production, contributing to resource conservation and waste reduction [6, 7]. Divsholi et al. [8] concluded that the substitution of cement with up to 50% of Ground Granulated Blast Furnace Slag (GGBS) resulted in a marginal enhancement of compressive strength due to the greater fineness of GGBS compared to Portland cement. Chofore et al. [9] used cement with an over-shelf life. In this particular mix, the blend of cement with GGBS up to 25% showed better results with an increment of 15.55% and 12.85% in strength than control concrete at 7 and 28 days, respectively. It has also been demonstrated that using finer supplementary cementitious materials (SCMs) compared to regular ones can significantly enhance the strength of concrete mixtures. To make them finer, they are usually ground fine or ultrafine to produce ultrafine SCMs, increasing their reactivity and surface area [10, 11]. Zhang et al. [12] and Zhu et al. [13] found that ultrafine slag refined the pore structure and enhanced the reactivity. Teng et al. [14] stated that compressive and flexural strength for Ultrafine Ground Granulated Blast Furnace Slag (UGGBS) up to 30% exhibited better strength results than the control mix at 28 days. Similar results were

noticed by Liu et al. [15], where UGGBS significantly improved pore size distribution in the concrete matrix and ultimately 28 days compressive strength. In another study, Zhou et al. [16] noted that the early rate of pozzolanic reactivity of UGGBS was up to 60% more than usual GGBS due to its increased fineness. Ghasemalizadeh et al. [17] observed that samples including 40% UGGBFS as a traditional cement substitute exhibited 10% higher compressive strength than the reference samples at 1, 3, 7, and 28 days and comparable strength at 91 days of duration. Therefore, the utilization of this industrial steel waste reduces greenhouse gas emissions associated with cement manufacturing while enhancing the performance of concrete [18–20].

1.2. Valorization of agricultural waste in cementitious materials

In addition to industrial residues, agricultural waste management is another critical area requiring attention. Agricultural waste constitutes a significant proportion of global waste and, when managed effectively, can serve as a valuable resource [21]. Research suggests that recycling agricultural waste has the potential to meet up to 25% of crop nutrient requirements [22]. Common agricultural waste materials include excretory waste from cattle, residual grains, and crops. The byproduct of rice milling is rice husk ash (RHA), which has been considered for its versatile applications [23, 24]. The author Ahsan et al. [25] noted that by replacing a portion of cement with RHA, the industry can cut CO₂ emissions and divert an agro-waste from landfills. For instance, RHA is extensively used in producing bricks, cement, and steel, contributing to resource conservation and waste minimization [26, 27]. Notably, the replacement of cement with RHA in concrete leads to improvement in the characteristics of concrete in terms of strength [28] and durability [29–31]. This would further help to resolve the challenges associated with the disposal of waste [32, 33]. While some studies indicate optimal performance at 10% RHA replacement, others report significant strength gains at 20% replacement [34]. In another study by Zerbino et al. [35], the partial substitution of cement with RHA up to 25% yielded a similar strength performance to traditional concrete. However, Park et al. [36] observed that 20% RHA content initially lowers the strength at 3 and 7 days due to the absorption of water by RHA particles. The absorption of water by the RHA particles further leads to a decreased hydration process at the initial stage. However, as hydration progresses, the water absorbed by the RHA particles diffuses into

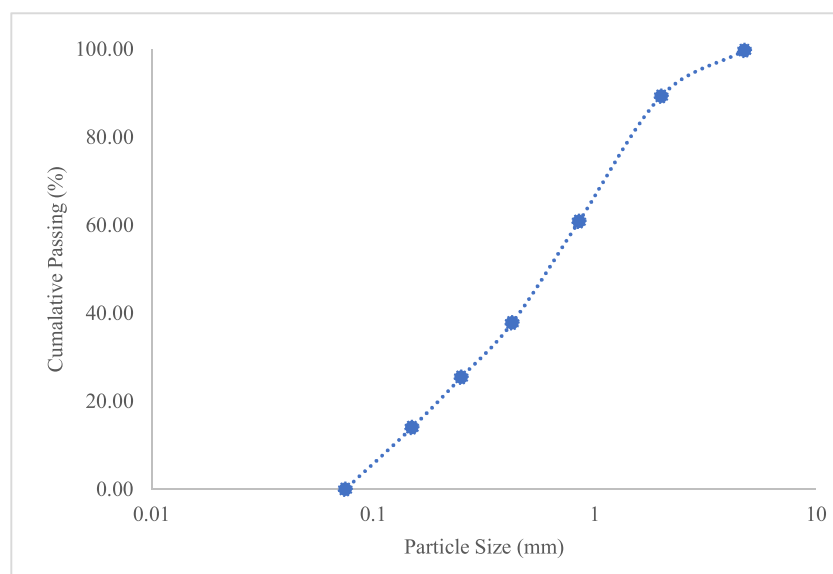


Fig. 1. Particle size distribution of crushed sand.

the cement matrix, thereby promoting hydration and enhancing compressive strength. The water absorbing characteristics of RHA are also discussed by Singh et al. [37]. Specifically, Siddika et al. [38] found that when the cement was substituted with 15% RHA, the compressive strength was depleted by 11.56%.

The use of RHA as a cement substitute in conventional concrete has been thoroughly studied in terms of mechanical strength, durability, and physical properties. However, minimal research on RHA-based binary, ternary, and blended mortar was observed in the literature review. This investigation focuses on the performance of partial replacement of cement with RHA (10, 15, and 20%), GGBS (20, 25, and 30%), and UGGBS (10%) in mortar mixes. The different water to binder (w/b) ratios and flow properties of mortar mix were examined. Further, the study was extended to understand the mechanical performance of mortar mixes.

2. Research significance

Despite extensive research on rice husk ash (RHA) and slag in the context of concrete, the majority of investigations predominantly concentrate on concrete, with limited studies exploring blended waste substitutes within mortar formulations. Particularly, a significant gap exists in the literature regarding binary (cement combined with one SCM) and ternary (cement combined with two SCMs) mixes that incorporate RHA, especially in mortar applications. Mortars may demonstrate different behaviors compared to concrete, owing to their finer aggregate and

binder ratios. Therefore, it is essential to understand how RHA, GGBS, and ultrafine GGBS affect the fresh and hardened properties of mortar.

The present study systematically examines mortar mixtures incorporating partial cement replacement with RHA (10%, 15%, 20%), GGBS (20%, 25%, 30%), and a UGGBS (10%). The investigation encompasses both the fresh-state properties and the mechanical performance of hardened mortar. This research investigates how different SCMs, when incorporated into controlled mortar mixes, affect workability and strength by examining the interaction between agricultural and industrial waste materials. This study aims to develop sustainable mortars that minimize the use of natural resources and reduce waste problems.

3. Materials and methods

3.1. Material characteristics

The materials used for the preparation of mortar mix are OPC (Grade 53) [39], GGBS [40], UGGBS [41], RHA, Crushed sand, and tap water. The fineness modulus of crushed sand was 2.7, which lies between the usual range of 2 to 4. The particle size distribution of crushed sand is shown in the Fig. 1. Tables 1 to 4 represent the chemical and physical characteristics of the OPC, GGBS, UGGBS, and RHA, respectively. The Neutrol-115 (PCE-based Superplasticizer) was used in this study. The morphological analysis of cement, GGBS, UGGBS, and RHA was made through a Scanning Electron Microscope (SEM) (Figs. 2 to 5).

Table 1. Chemical and physical characteristics of OPC 53 grade.

Chemical Content	% Content
Al ₂ O ₃ /Fe ₂ O ₃	1.15
Magnesia	0.91
Sulphuric Anhydride	2.2
Chloride	0.013
Loss on Ignition (LOI)	2.23
Insoluble Residue	2.05
Lime Saturation Factor (LSF) [(CaO–0.7SO ₃)/((2.8 SiO ₂ + 1.2Al ₂ O ₃ + 0.65Fe ₂ O ₃)]	0.89
Properties Tested	Tested Results
Fineness by Blaine's (m ² /kg)	295
Standard Consistency (%)	28.75
Soundness:	
Le Chat Expansion (mm)	0.5
Autoclave Expansion (%)	0.04
Setting Time:	
Initial Setting Time	150
Final Setting Time	215

Table 2. Chemical and physical characteristics of GGBS.

Chemical Content	% Content
MnO (% by mass)	0.2
MgO (% by mass)	7.35
Sulphide Sulphur (% by mass)	0.48
SO ₃ (% by mass)	1.05
Insoluble Residue (% by mass)	1.57
Chloride (% by mass)	0.0035
Moisture Content (% by mass)	0.044
Loss on Ignition (% by mass)	The gain was observed (–0.35%)
Glass Content (%)	97.3
Properties Tested	Tested Results
Density (g/cc)	2.88
Fineness by Blaine's (m ² /kg)	368
Consistency (%) Control Specimen	25
Consistency (%) Test Specimen	30
7 days Slag Activity Index (%)	80
Retained on 45μ wet sieved (%)	0.87

Table 3. Chemical and physical characteristics of UGGBS.

Chemical Content	% Content
MnO (% by mass)	0.28
MgO (% by mass)	8.45
Sulphide Sulphur (% by mass)	0.48
Sulphate as SO ₃ (% by mass)	0.15
Insoluble Residue (% by mass)	0.36
Chloride (% by mass)	0.018
Moisture Content (% by mass)	0.05
Loss on Ignition (% by mass)	< 0.01
Glass Content (%)	90.2
Properties Tested	Tested Results
Specific Gravity	2.86
Fineness by Blaine's (m ² /kg)	1826
Consistency (%) Control Specimen	25
Consistency (%) Test Specimen	30
7 days Slag Activity Index (%)	110
Particle Size (μm maximum)	
D ₅₀	4.31
D ₉₅	14.59

Table 4. Chemical and physical characteristics of rice husk ash.

Chemical Content	% Content
SiO ₂	92.5
Al ₂ O ₃	2.5
Fe ₂ O ₃	2.20
Na ₂ O + K ₂ O	0.68
CaO	0.23
Loss on drying at 100°C	4.02
Properties Tested	Tested Results
Specific Gravity	2.26
Bulk Density	0.24

3.2. Preparation of mortar mixtures

A total of 32 mortar mixes were prepared for this study. The cementitious materials like RHA, GGBS, and UGGBS were partially replaced by cement (% by weight), and all the combinations are listed in the Table 5.

3.3. Methodology for the tests

Mortar Flowability was evaluated with the help of a flow table test (Fig. 6) as per ASTM C1437 [42]. The flow was assessed to investigate the flowability of the mortar mixture after every 15 minutes for 1 hour.

The determination of the mechanical characteristics of any specimen aims to check its performance under different loads. In this context, 50 mm cubes were subjected to a compression test in compliance with ASTM C109 [43] as shown in Fig. 7(a). Seventy-five cube specimens were tested for 28 days. The determination of bending stress was also made to evaluate the ductile behavior. A prism-shaped mortar specimen of 40×40×160 mm is filled in two layers that undergo 3-point stress. Flexural strength tests were performed on 75 prism specimens. All prism specimens underwent 3-point bending testing following ASTM C348 at 28 days [44], as shown in Fig. 7(b).

4. Results & Discussion

4.1. Fresh properties of blended mortar

The flow table test was conducted to evaluate the workability and cohesiveness of the mortar mixes. This method provides valuable insights into the fresh-state behavior of mortar, particularly in terms of its ability to deform and flow under minimal compaction. Higher flow values indicate a more fluid and workable mix, while lower values are typically associated with increased stiffness and reduced mobility. In this study, the average spread diameters were targeted within a controlled range of approximately

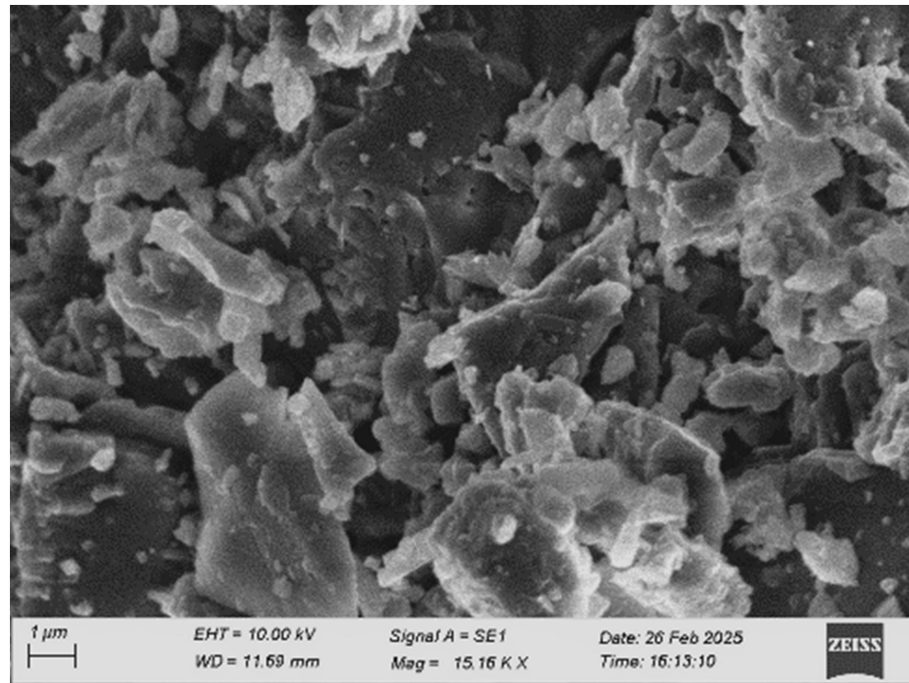


Fig. 2. SEM-Microphotograph of cement.

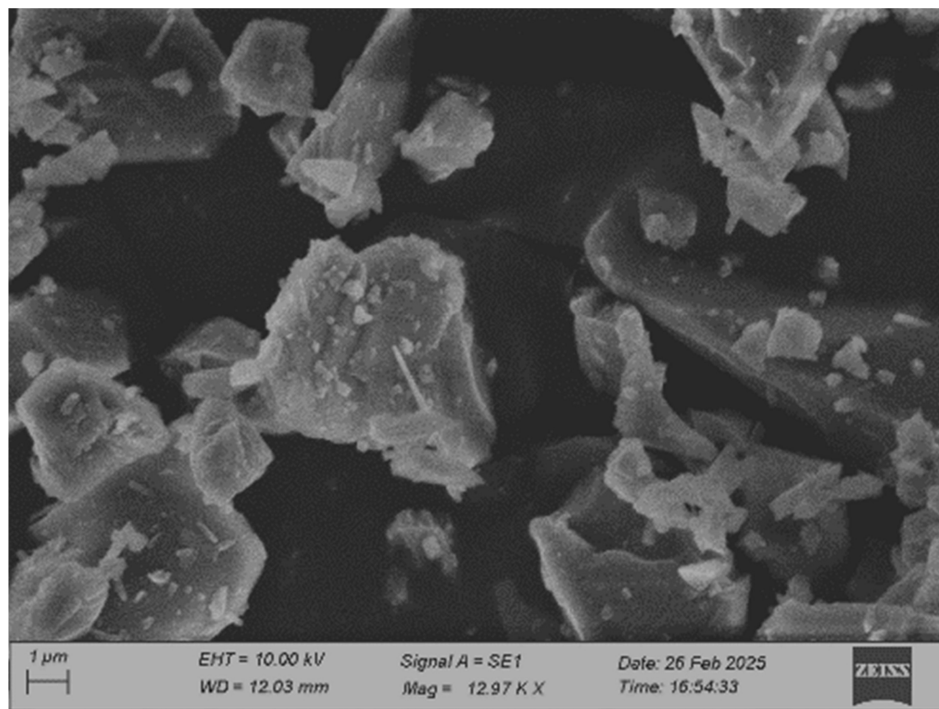


Fig. 3. SEM-Microphotograph of GGBS.

200 ± 20 mm to ensure consistency across mixes and to minimize the risk of segregation or bleeding.

The results also offered indirect evidence of internal cohesion among particles, as mixtures with lower flow values tended to exhibit higher viscosity and

potential resistance to deformation. This behavior is significant in mortar systems containing SCMs, where the balance between water demand, particle interaction, and admixture dosage significantly influences the fresh-state performance.

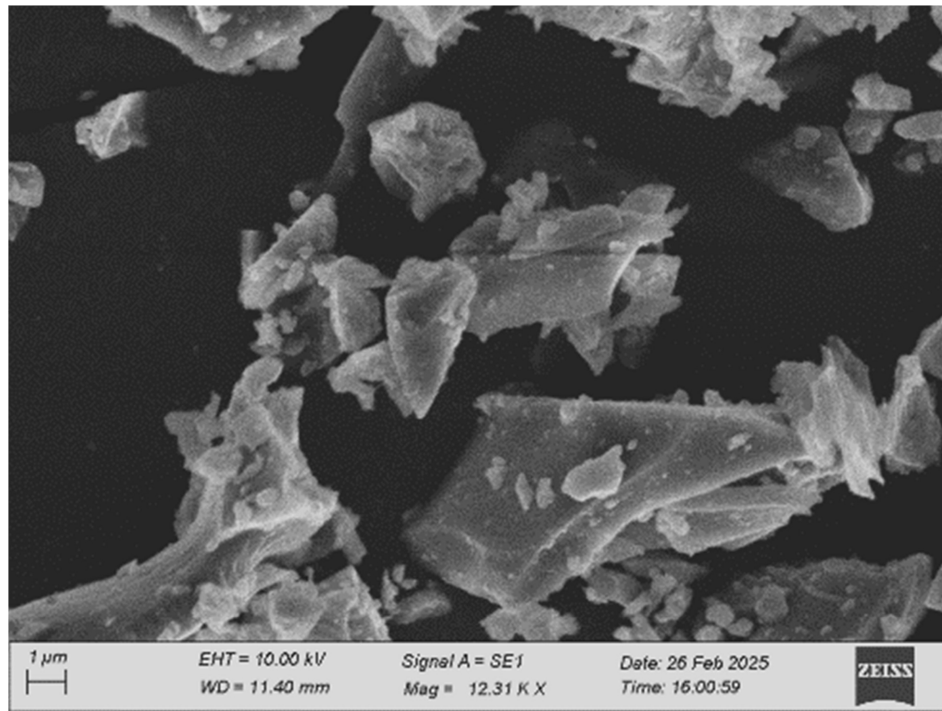


Fig. 4. SEM-Microphotograph of UGGBS.

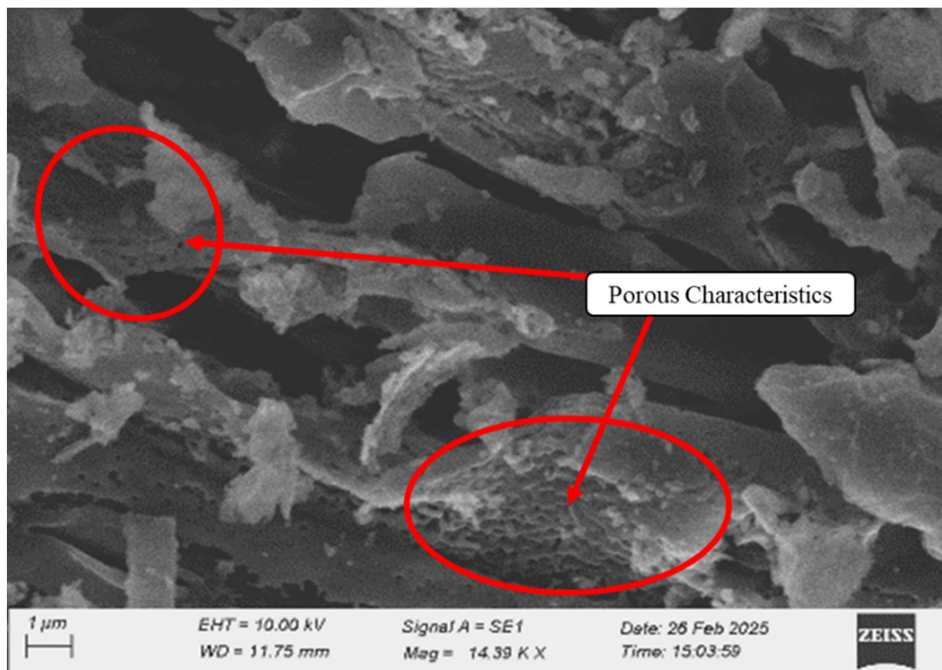


Fig. 5. SEM-Microphotograph of RHA.

Fig. 8 presents the flow table values of binary mortar mixes incorporating GGBS and RHA as partial replacements for cement. Mixes D2 to D4 (G20 to G30) demonstrated enhanced initial flowability ($t = 0$ min) compared to the control mix (D1), despite employing

lower w/b ratios. The G20 mix (D2) achieved an initial flow of 198 mm with a w/b ratio of 0.308, compared to 183 mm for the control mix at a higher w/b of 0.332. This improvement is attributed to the latent hydraulic properties and smoother particle texture

Table 5. Binder composition (% by weight) for mortar preparation.

Mix ID	Mix Combination	Cement (wtg.)	GGBS (wtg.)	UGGBS (wtg.)	RHA (wtg.)	Water/Binder	Admixture (g)
D1	Control Mix	100	0	0	0	0.332	0
D2	G20	80	20	0	0	0.308	3
D3	G25	75	25	0	0	0.307	3
D4	G30	70	30	0	0	0.305	3
D5	R10	90	0	0	10	0.345	3
D6	R15	85	0	0	15	0.388	3
D7	R20	80	0	0	20	0.415	3
D8	UG10	90	0	10	0	0.308	3
D9	G20 UG10 R0	70	20	10	0	0.307	3
D10	G25 UG10 R0	65	25	10	0	0.295	3
D11	G30 UG10 R0	60	30	10	0	0.283	3
D12	UG10 R10	80	0	10	10	0.359	6
D13	UG10 R15	75	0	10	15	0.32	6
D14	UG10 R20	70	0	10	20	0.481	7.5
D15	G20 R10	70	20	0	10	0.347	6
D16	G20 R15	65	20	0	15	0.415	6
D17	G20 R20	60	20	0	20	0.492	6
D18	G25 R10	65	25	0	10	0.446	6
D19	G25 R15	60	25	0	15	0.461	6
D20	G25 R20	55	25	0	20	0.469	8
D21	G30 R10	60	30	0	10	0.351	6
D22	G30 R15	55	30	0	15	0.405	6
D23	G30 R20	50	30	0	20	0.446	9
D24	G20 UG10 R10	60	20	10	10	0.328	6
D25	G20 UG10 R15	55	20	10	15	0.369	6
D26	G20 UG10 R20	50	20	10	20	0.461	6
D27	G25 UG10 R10	55	25	10	10	0.369	6
D28	G25 UG10 R15	50	25	10	15	0.4	6
D29	G25 UG10 R20	45	25	10	20	0.422	9
D30	G30 UG10 R10	50	30	10	10	0.369	6
D31	G30 UG10 R15	45	30	10	15	0.4	6
D32	G30 UG10 R20	40	30	10	20	0.398	9

Note: R = RHA, G = GGBS, UG = UGGBS, % = Percentage, wgt. = % by weight, g = gram.

**Fig. 6.** Assessment of flow through the flow table.

of GGBS, which can enhance flow while maintaining cohesion. However, all GGBS mixes exhibited a gradual decline in spread diameter over time, with final values converging around 158–160 mm after 60 minutes, indicating moderate workability retention.

Conversely, mixes incorporating RHA (D5 to D7) required substantially higher w/b ratios (0.345 to

0.415) to achieve initial flow values close to 190 mm. Despite this adjustment, these mixes exhibited rapid loss in flow values within 60 minutes, with the final spread reducing to as low as 142 mm for the R20 mix (D7). This sharp decline is attributed to the highly porous and amorphous nature of RHA (as visible in Fig. 5), which promotes increased water absorption

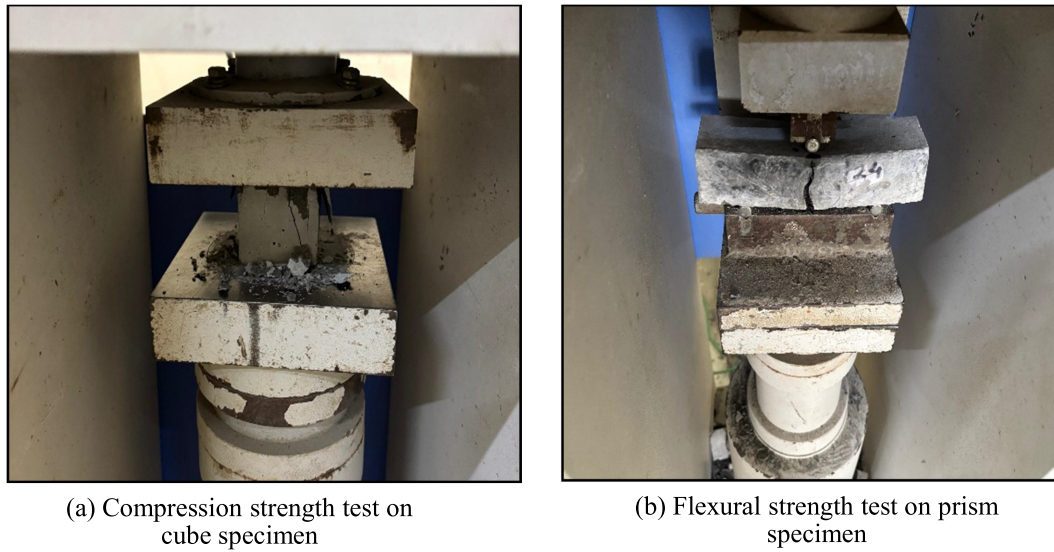


Fig. 7. Mechanical testing of specimens.

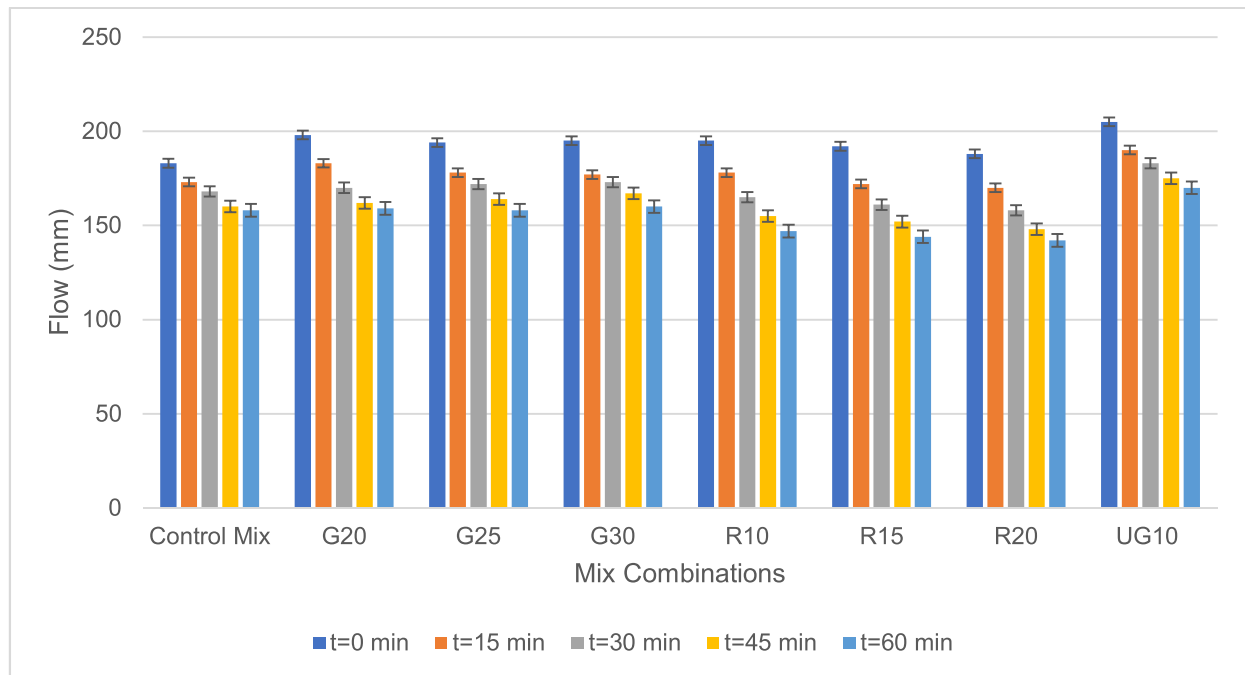


Fig. 8. Flow table values for the mixes containing only G & only R.

and internal curing effects. Notably, the 10% UGGBS mix (D8) exhibited the highest flow retention, maintaining a flow of 170 mm at 60 minutes, suggesting that UGGBS can offer improved rheological stability due to enhanced particle packing and reduced inter-particle friction.

Fig. 9 presents the flow characteristics of ternary mortar blends incorporating varying levels of GGBS (20–30%) along with 10% UGGBS, designated as D9 to D11. Compared to the control mix (D1), all ternary

mixes exhibited higher initial flow values despite lower w/b ratios, indicating improved workability. For instance, the D11 mix (G30 + UG10) achieved an initial spread diameter of 195 mm with a w/b ratio of 0.283, compared to 183 mm for the control mix with a w/b of 0.332. This suggests that the inclusion of UGGBS, due to its finer particle size and enhanced surface area (Fig. 4), improves particle packing and reduces internal friction, thereby enabling better flowability at reduced water demand.

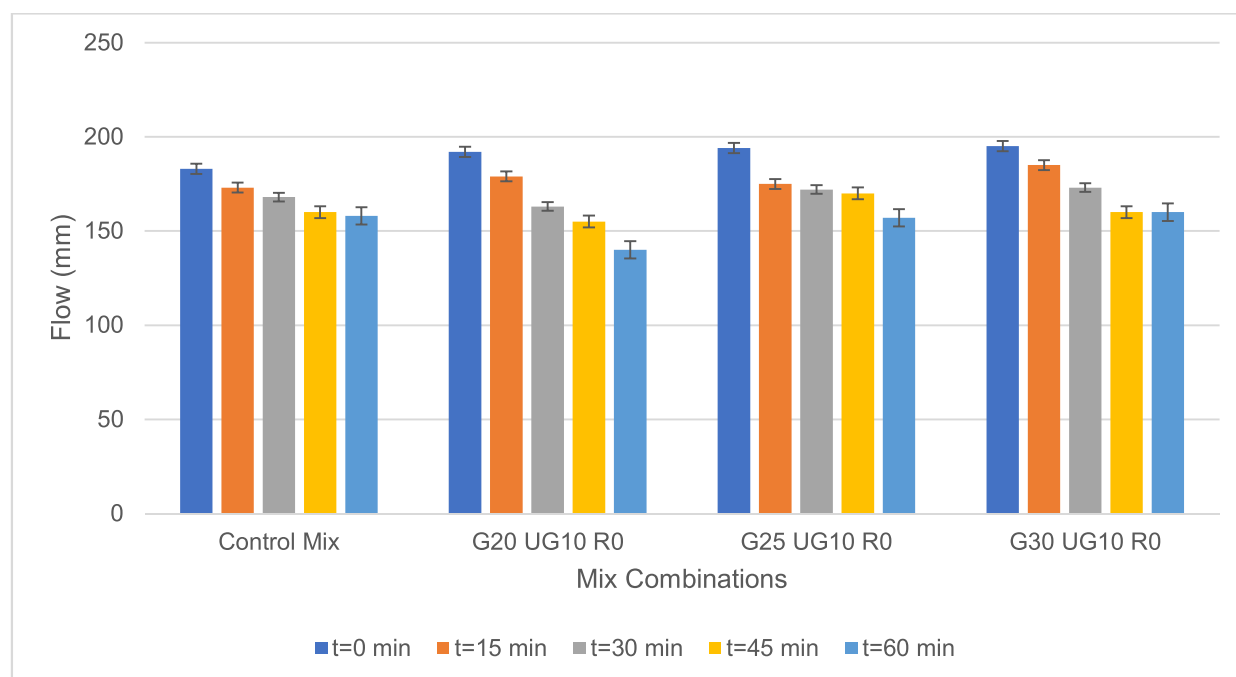


Fig. 9. Flow table values for G & UG combination.

Another study reported similar observations [17], which highlighted the dispersive and filler effects of UGGBS in enhancing rheological performance.

The retention of flow over time also demonstrated notable improvements in mixes containing UGGBS. After 60 minutes, the spread diameters remained between 140 mm and 160 mm, which, although lower than the initial values, indicate relatively stable rheological behavior compared to RHA-based mixes. Notably, mix D10 (G25 + UG10) retained a high degree of workability, with a decline in spread from 194 mm to 157 mm over one hour. This enhanced stability can be attributed to the synergistic interaction between GGBS and UGGBS, where the latter provides both a nucleation site for early hydration and a densified microstructure that delays stiffening. The results demonstrate that blending GGBS with UGGBS not only reduces the need for high water content but also ensures more consistent workability over extended periods. This highlights the potential of UGGBS as an effective rheology-modifying agent in a sustainable mortar system.

The flow variation for mortar mixes incorporating 10% UGGBS combined with varying levels of RHA was also studied (Fig. 10) where it was observed that mix D8, which included only 10% UGGBS, exhibited superior flow performance across all time intervals, maintaining a spread diameter of 170 mm after 60 minutes with a relatively low w/b ratio of 0.308. This highlights the positive effect of UGGBS on

fresh-state workability due to its ultrafine particle size and enhanced dispersion capability, which contribute to better packing density and reduced interparticle friction [45].

However, the inclusion of RHA alongside UGGBS (Mixes D12–D14) resulted in notable reductions in flow retention. The D12 mix (UG10 R10) showed a significant decrease in flow from 195 mm (at $t = 0$ min) to 140 mm (at $t = 60$ min), despite a higher admixture dosage and an increased w/b ratio of 0.359. This trend was more pronounced in mix D13, where the use of 15% RHA with a reduced w/b ratio (0.32) led to a steep decline in flow to 124 mm after 1 hour. D14, with 20% RHA, required the highest w/b ratio (0.481) and an admixture dosage of 7.5 g to achieve an acceptable initial flow; yet, it still experienced a substantial decline in workability over time.

These results confirm the adverse impact of RHA on fresh mortar rheology when used at higher dosages, even in the presence of flow-enhancing SCMs, such as UGGBS. The findings corroborate the conclusions of Almutlaqah et al. [46], who emphasized the critical need to control RHA content and optimize mix proportions to offset its high water demand.

Fig. 11 summarizes the flow behavior of mortar mixes incorporating conventional GGBS and varying proportions of RHA. The mixes were grouped to assess the effect of increasing RHA content (20%) at constant GGBS levels (20%, 25%, and 30%). A consistent trend was observed across all GGBS levels, where

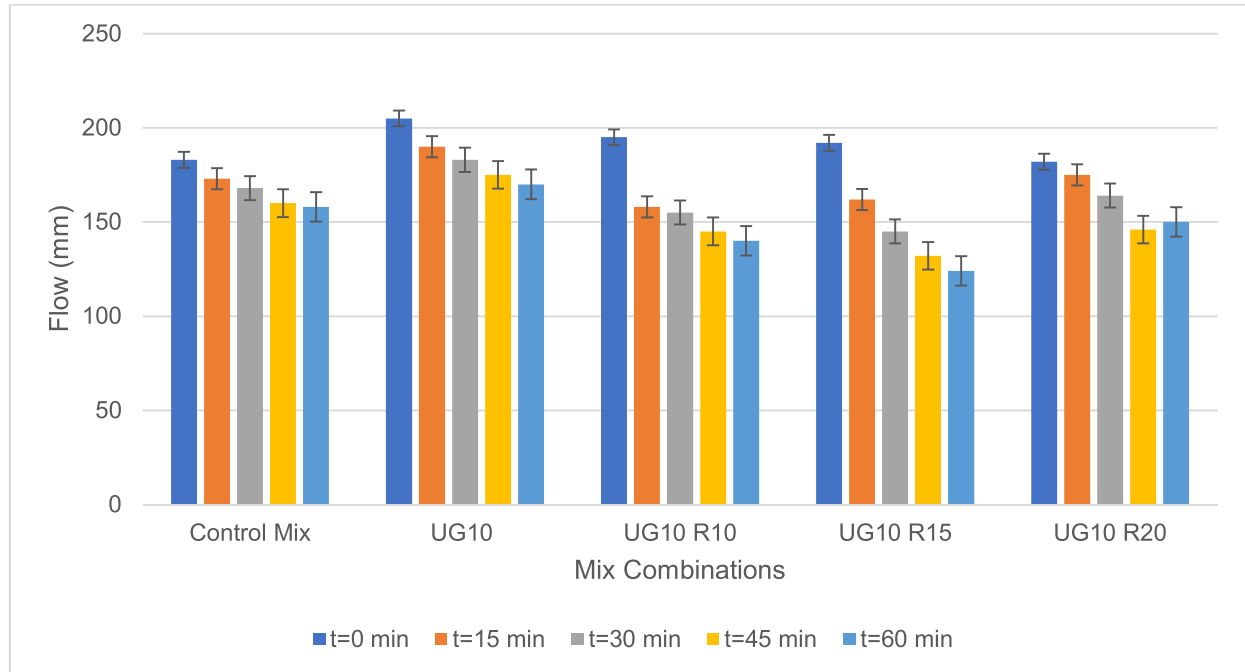


Fig. 10. Flow table values for UG & R combination.

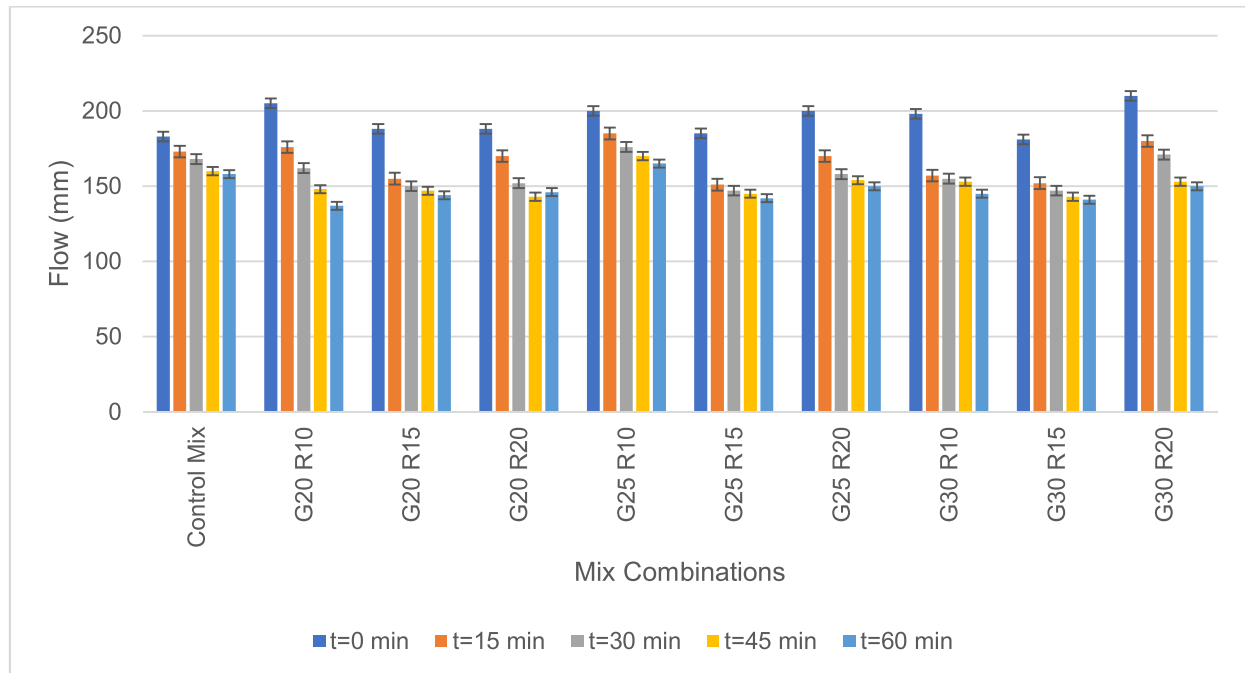


Fig. 11. Flow table values for G & R combination.

higher RHA content led to increased w/b ratios to achieve comparable initial flow. For instance, Mix D15 (G20 R10) achieved an initial flow of 205 mm with a w/b ratio of 0.347, while D17 (G20 R20) required a significantly higher w/b ratio of 0.492 to maintain similar flowability. Despite the additional water, D17 experienced a sharp reduction in flow

over 60 minutes (to 146 mm), indicating poor workability retention. These trends confirm that the porous morphology and high surface area of RHA significantly increase water demand and adversely affect flow retention.

In the 25% GGBS mixes (D18-D20), initial flow values did not consistently increase with rising w/b

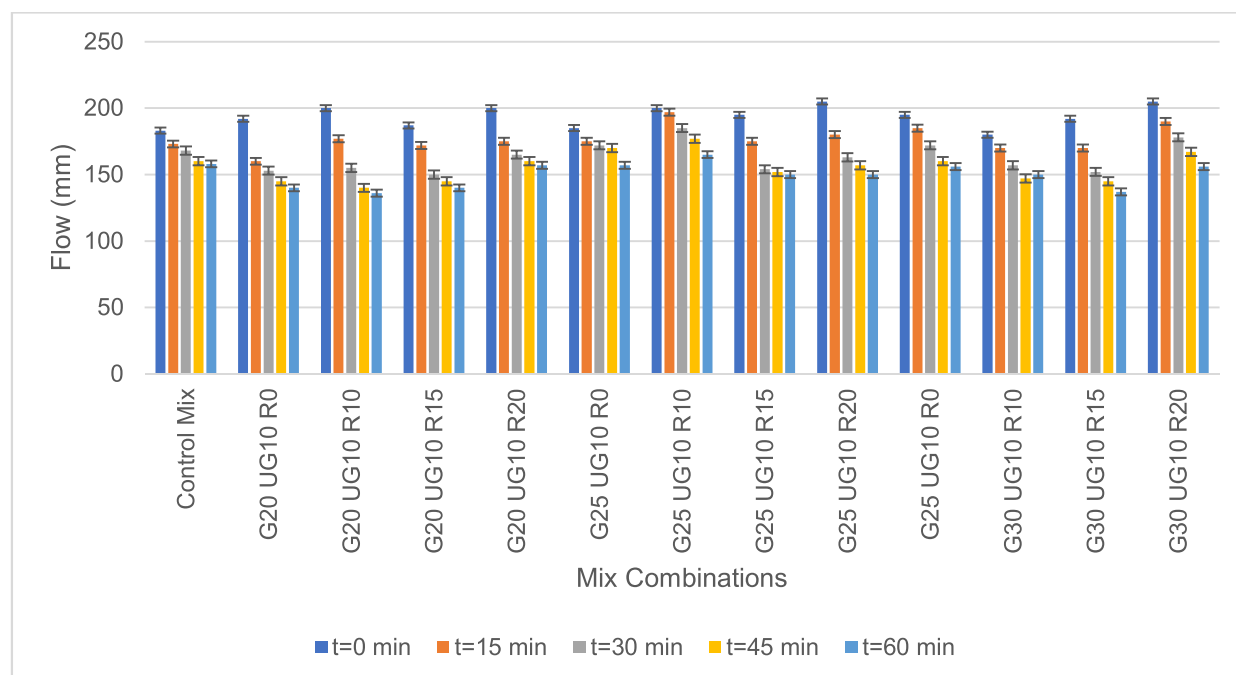


Fig. 12. Flow table values for G, UG & R combination.

ratios, particularly in D19 (R15%), where a w/b ratio of 0.461 yielded a lower flow than D18, despite the same admixture dosage. This non-linear response suggests that beyond a specific content, increasing RHA content impairs particle dispersion, possibly due to internal water sequestration and early stiffening effects. The D20 mix, which included an additional admixture (8 g), was able to restore flow to 200 mm, highlighting the need for both water and chemical admixture to compensate for the absorption capacity of RHA.

For the 30% GGBS mixes (D21–D23), a similar pattern was noticed. While the w/b ratio remained relatively constant (0.446–0.461), the increase in admixture dosage in mix D23 (9 g) enabled the flow to reach 210 mm, outperforming D21 and D22. These findings highlight that at higher SCM replacement levels, particularly with RHA, achieving sufficient flow necessitates a balanced approach that incorporates both water and admixture adjustments.

After evaluating the binary and ternary blended combinations, the advantages and disadvantages of employing various SCMs for preparing mortar mixtures were noted. However, to further understand the influence of quaternary blended mortar mix, we have done some trials, and the results are shown in the Fig. 12.

Fig. 12 presents the flow behavior of quaternary blended mortars incorporating GGBS, UGGBS, and RHA. The inclusion of 10% UGGBS and 20–30%

GGBS at a constant admixture dosage demonstrated that the initial flow values for the mixes without RHA (D9–D11) fall within the expected range. However, when RHA was introduced, a higher w/b ratio was necessary to achieve acceptable flow values. For example, mix D24 (G20 UG10 R10) required a w/b ratio of 0.328 to achieve a 200 mm flow, while mix D25 (RHA increased to 15%) showed a reduced flow of 187 mm, despite a higher w/b ratio of 0.369. This inverse relationship reflects the water-absorbing nature and irregular particle morphology of RHA (Fig. 5), which increases internal friction and reduces adequate free water in the mix [33, 47].

To mitigate this loss in flow with increased RHA content, further adjustments were made to both water content and admixture dosage. In mixes D26 and D29, higher w/b ratios (0.461 and 0.422, respectively) were combined with increased admixture dosages (from 6 g to 9 g), which successfully restored initial flow to approximately 200 mm. This emphasizes the importance of simultaneously adjusting both water and chemical admixture when incorporating high levels of RHA. Interestingly, even with similar w/b and admixture content, mix D30 (G30 UG10 R10) exhibited lower initial flow than D27 (G25 UG10 R10), indicating that exceeding 25% GGBS replacement may compromise fresh-state flow.

Across all quaternary mixes, a consistent decline in flowability was observed over a 60-minute period, with spread diameters eventually stabilizing between

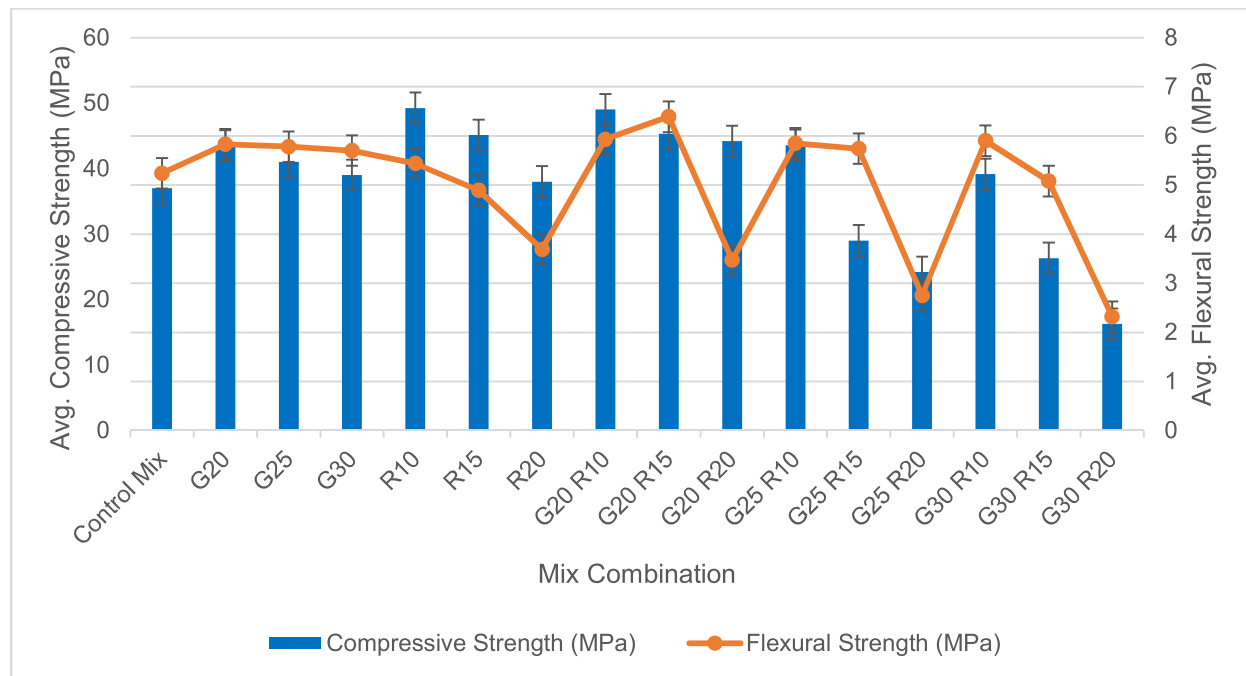


Fig. 13. Results for hardened properties of blended mortar for G & R combination.

140 mm and 157 mm. The reduction in flow with rest time is attributed to continued hydration reactions, moisture loss, and increased cohesiveness due to RHA's absorptive behavior. Overall, while UGGBS aids in enhancing early workability, the combined presence of RHA demands careful proportioning of water and admixture to maintain performance. These findings highlight the complexity between different SCMs and the need for tailored mix designs to optimize flow characteristics in multi-blended cementitious systems.

4.2. Variation in compressive strength (CS) of mortar samples

All the 96 specimens (3 cubes each for 32 mixes) for compression tests were tested for 28 days. The performance of different mix combinations under which cement has been partially replaced with RHA, GGBS, and UGGBS is discussed in this section.

4.2.1. Compressive strength of binary and ternary blends (Cement, GGBS, RHA)

Fig. 13 presents the 28-day compressive strength (CS) results for mixes incorporating GGBS and RHA as partial cement replacements.

- **Binary GGBS Blends (D2-D4):** Replacing cement with GGBS in proportions ranging from 20% to 30% generally led to an increase in CS compared to the control mix (D1), which had a CS

of 37.01 MPa. Specifically, the G20 mix (D2) achieved the highest strength in this series at 43.5 MPa, demonstrating an approximately 17.5% increase over the control. While G25 (D3) and G30 (D4) showed slight reductions in strength compared to D2, their values (41 MPa and 39 MPa, respectively) remained higher than the control mix. This trend suggests an optimal GGBS replacement level of around 20% for these binary blends.

- **Binary RHA Blends (D5-D7):** Similarly, the incorporation of RHA from 10% to 20% replacement levels also resulted in increased CS compared to the control mix. The R10 mix (D5) exhibited the most significant improvement, achieving 49.25 MPa, which is a remarkable 33.07% increase over the control. As the RHA content increased to 15% (D6, 45.13 MPa) and 20% (D7, 38 MPa), the strength showed a decreasing trend from the optimal 10% level, though D7 still slightly surpassed the control mix.

- **Ternary Blend of GGBS & RHA (D15-D23):** The study then explored ternary combinations involving both GGBS and RHA. Notably, mixes D15 (G20 R10, 49.03 MPa) and D16 (G20 R15, 45.32 MPa), incorporating 20% GGBS with 10% and 15% RHA, respectively, showed comparable or superior strength to the binary RHA mix (D5) and significantly outperformed the control. Mixes D17 (G20 R20, 44.2 MPa) and D18 (G25 R10, 43.58 MPa) also demonstrate strengths higher than the control. However, a reduction in CS was

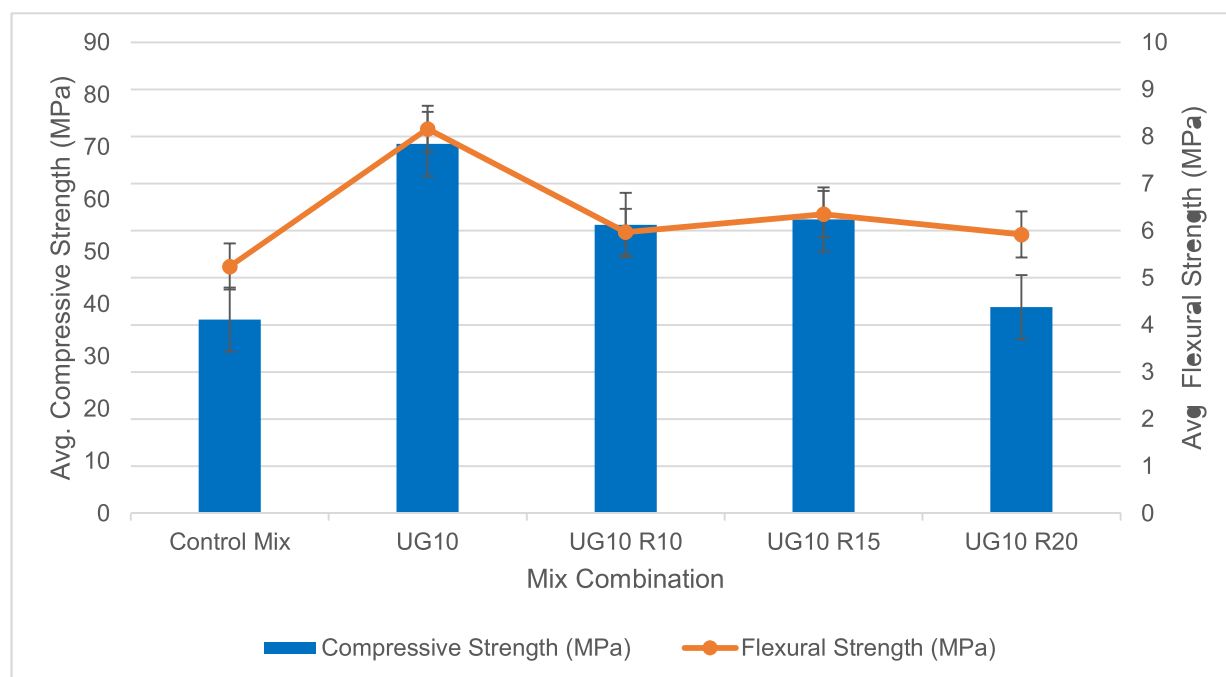


Fig. 14. Results for hardened properties of blended mortar for UG & R combination.

observed for mixes D19 to D23. For instance, D19 (G25 R15) recorded a strength of 29.01 MPa, significantly lower than the control, and this decline was more drastic with increasing RHA content, culminating in D23 (G30 R20) at 16.28 MPa.

The enhanced compressive strength observed in binary blends with optimal GGBS (D2) and RHA (D5) is consistent with their known pozzolanic and latent hydraulic properties. GGBS reacts with CH produced during cement hydration, forming an additional C-S-H gel that densifies the microstructure and improves strength, particularly at later ages. Similarly, RHA, rich in amorphous silica, also undergoes a pozzolanic reaction, consuming CH to form more C-S-H.

The peak strength at 10% RHA (D5) aligns well with findings in existing literature. For instance, studies by Siddika et al. [38] reported an optimal RHA replacement level around 10–15%, beyond which the benefits diminish or strength can decrease. This is often attributed to the porous nature of RHA particles (as indicated in Fig. 5). While RHA contributes to the filler effect and pozzolanic activity to some extent, excessive porous RHA can absorb a significant amount of mixing water, reducing the effective w/b ratio for cement hydration and creating more voids within the matrix, thereby compromising strength. This phenomenon is evident in the current results as the water/binder ratio generally increased with higher RHA content (e.g., D5 with w/b 0.345 vs. D7 with w/b 0.415), suggesting the need for more water

to maintain workability despite the presence of more porous RHA.

The performance of the ternary blends further highlighted this balance. Mixes with lower RHA content (D15–D18) generally maintain strengths above the control, indicating the combined synergistic effect of GGBS and RHA. However, the drastic reduction in strength for mixes D19 to D23, particularly those with 15% and 20% RHA (e.g., D19, D20, D22, D23), underscores the detrimental impact of excessive RHA.

The high replacement levels, coupled with the porous nature of RHA, likely resulted in insufficient water for complete hydration and a less dense matrix, which severely impacted compressive strength. This observation suggests that in multi-component systems, the individual contributions and potential drawbacks of each SCM must be carefully balanced.

4.2.2. Compressive strength of binary and ternary blends with Ultrafine GGBS

Fig. 14 presents the 28-day CS results for mixes incorporating Ultrafine GGBS (UG) and RHA.

- **Binary UGGBS Blend (D8):** The introduction of UGGBS had a profound positive effect on compressive strength. The UG10 mix (D8), which replaces 10% of the cement with UGGBS, achieved a strength of 70.58 MPa. This represents a significant increase in strength compared to the control mix (D1).

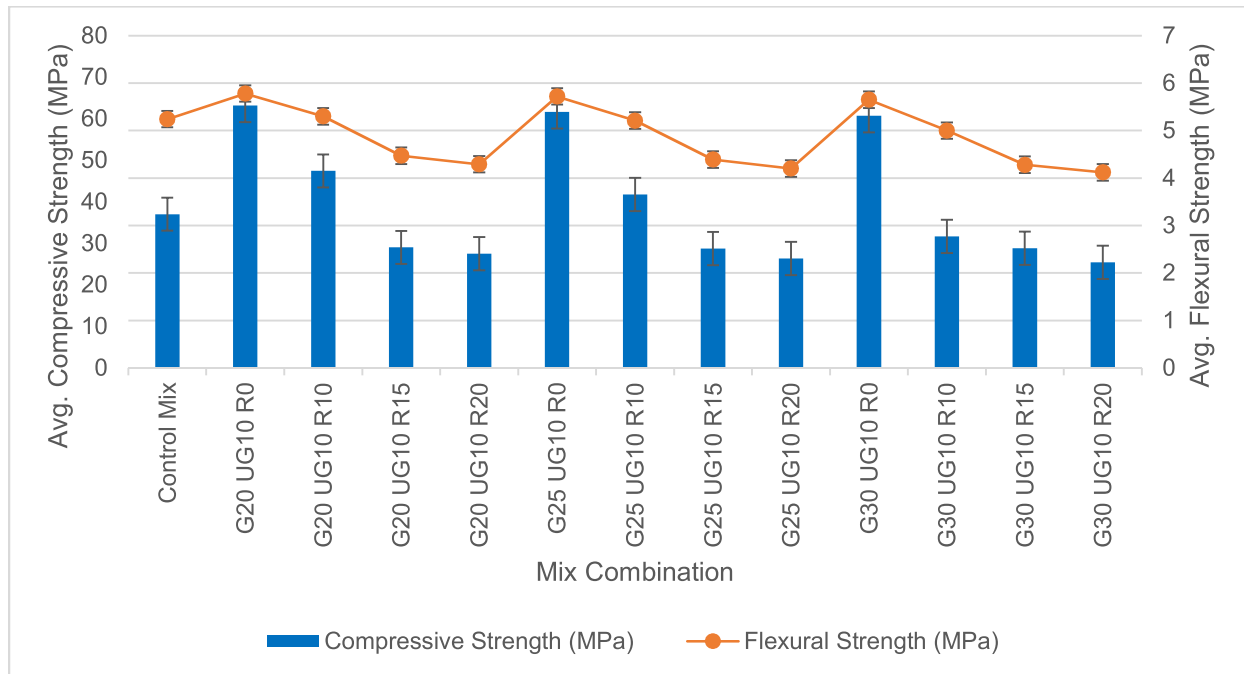


Fig. 15. Results for hardened properties of blended mortar for G, UG & R combination.

- **Ternary Blends (UG & RHA, D12-D14):** When UG was combined with RHA, the strengths remained significantly high compared to the control. D12 (UG10 R10) and D13 (UG10 R15) achieved 55.11 MPa and 56.13 MPa, respectively, both substantially higher than the control and even the best binary RHA mix (D5). However, increasing the RHA content to 20% in D14 (UG10 R20) resulted in a noticeable drop to 39.38 MPa, although this is still better than the control mix.

The remarkable increase in compressive strength resulting from the incorporation of Ultrafine GGBS (UG) is attributed to the enhanced fineness of UG particles (Fig. 4). Ultrafine particles effectively fill the micropores and voids within the cement paste, contributing to a denser, and more homogeneous mortar matrix. This pore refinement significantly reduces permeability and increases mechanical strength. The larger surface area of ultrafine particles provides more sites for pozzolanic reactions to occur and acts as a nucleation site for the formation of C-S-H gel. This accelerates and enhances the hydration process, leading to a more developed and stronger microstructure. Teng et al. [14] also observed that increased fineness of SCMs like GGBS leads to improved hydration kinetics and higher compressive strengths by refining the pore structure and enhancing C-S-H formation.

When UGGBS was combined with RHA (D12-D14), the strength was found to be high, demonstrating

the effectiveness of UG. The UG10 R15 (D13) mix with 56.13 MPa strength is particularly noteworthy, indicating that even with 15% RHA, the positive impact of UG can overcome some of RHA's potential drawbacks. However, the subsequent drop in strength for D14 (UG10 R20) reinforces the earlier observation regarding high RHA content. Despite the benefits of UG, a 20% replacement level of porous RHA still negatively affects strength by increasing water demand and potentially disrupting the optimized microstructure formed by UG and cement.

4.2.3. Compressive strength of quaternary blends (Cement, GGBS, UGGBS, RHA)

Fig. 15 presents the 28-day CS results for mixes incorporating a quaternary blend of cement, GGBS, UGGBS, and RHA.

- **Ternary Blends with GGBS & UGGBS, 0% RHA (D9-D11):** Initially, mixes D9 (G20 UG10 R0), D10 (G25 UG10 R0), and D11 (G30 UG10 R0), which combine GGBS and UGGBS without RHA, showed high strengths: 63.14 MPa, 61.65 MPa, and 60.69 MPa, respectively. These values significantly exceed those of the control mixture (D1) and even surpass the highest performing binary GGBS mixture (D2), demonstrating a strong synergy between GGBS and UGGBS.
- **Quaternary Blends (G, UG, R, D24-D32):** When RHA was introduced into these G & UG blends,

the impact on strength varied significantly with the RHA content.

- Mixes D24 (G20 UG10 R10 with 47.42 MPa strength) and D27 (G25 UG10 R10 with 41.74 MPa strength), both containing 10% RHA, still exhibited higher strengths than the control mix (D1). D24, in particular, was among the highest performing quaternary blend.
- However, as the RHA content increased to 15% (e.g., D25, D28, D31) and 20% (e.g., D26, D29, D32), a consistent and significant drop in compressive strength was observed across all GGBS variations. For example, from D24 (47.42 MPa) to D26 (27.49 MPa), there was a substantial reduction in strength due to the increase in RHA. Similarly, D27 (41.74 MPa) decreased to D29 (26.33 MPa), and D30 (31.64 MPa) dropped to D32 (25.4 MPa).
- In other quaternary mixes with higher RHA content (D25, D26, D28, D29, D30, D31, D32), the compressive strength dropped below that of the control mix D1, indicating a detrimental effect from the combination of high SCM replacement and high RHA content.

The results from the quaternary blends confirm the potent positive influence of combining GGBS and UGGBS on mortar strength, as initially observed in mixes D9–D11. This synergistic effect is attributed to the complementary actions of the two GGBS forms: the normal-sized GGBS contributes to overall hydration and long-term strength, while the ultrafine GGBS provides immediate benefits through pore filling and enhanced early-age reactions.

However, the consistent pattern of decreasing compressive strength with increasing RHA content within these quaternary blends is a critical observation. Even with the highly beneficial presence of UGGBS, higher dosages of RHA (15% and 20%) negate the positive effects and lead to a significant reduction in strength, often below that of the control mix. The primary reason for this observed strength degradation at higher RHA levels is consistently linked to the porous nature of RHA particles (as illustrated in Fig. 5). These highly porous particles act as a water sink, absorbing a portion of the mixing water that would otherwise be available for cement and SCM hydration. This reduced w/b ratio at the micro-level leads to incomplete hydration, increased porosity, and a weaker ITZ within the mortar matrix, ultimately reducing compressive strength. This effect becomes more pronounced as the overall cement replacement by SCMs increases, as seen in mixes like D30–D32, where the

combination of high GGBS, UGGBS, and RHA replacement likely led to a significant dilution of OPC and water absorption issues from the RHA.

While GGBS and particularly UGGBS offer substantial improvements in mortar strength due to their pozzolanic activity, latent hydraulic properties, and particle packing effects, the inclusion of RHA requires careful optimization. An optimal RHA content (approximately 10% in these quaternary blends) can still yield strength superior to those of the control. However, exceeding this optimal level leads to a rapid decline in strength, primarily due to the inherent water absorption characteristics of RHA, which negatively impact the overall hydration process and densification of the mortar microstructure. Future research should investigate alternative RHA processing methods (e.g., finer grinding) or the use of superplasticizers to counteract the water absorption effect at higher RHA replacement levels.

4.3. Variation in flexural strength of mortar samples

This section discusses the performance of 32 mix combinations containing RHA, GGBS, and UGGBS, which partially replaced the OPC. All 96 specimens (3 prisms each for 32 mixes) were tested for flexural tests over 28 days.

4.3.1. Flexural strength of binary and ternary blends (Cement, GGBS, RHA)

Fig. 13 presents the 28-day flexural strength (FS) results for mixes incorporating GGBS and RHA as partial cement replacements.

- **Binary GGBS Blends:** The presence of GGBS from 20% to 30% significantly increased the FS compared to the control mix (D1). Specifically, the 20% replacement of cement with GGBS yielded the highest FS among these mixes. While increasing GGBS content beyond 20% led to a reduction in FS, the values remained higher than those of the control mix (D1).
- **Binary RHA Blends:** Conversely, as the percentage of RHA increased, FS diminished significantly. Mixes D6 (R15) and D7 (R20) reportedly resulted in lesser strength than the D1 control mix, suggesting that even moderate RHA levels can negatively impact the flexural performance of the binary blend.
- **Ternary Blends (GGBS & RHA):** To further reduce cement usage, blended combinations of GGBS and RHA were investigated. Mixes D15, D16, and D17, which had constant GGBS content (G20) but increasing RHA levels (R10, R15, R20), showed poorer FS with RHA content

exceeding 15%. This trend was also observed in the D18 (G25 R10), D19 (G25 R15), and D20 (G25 R20) mixes. The binders from D21 to D23, characterized by a minimal cement content and high percentages of SCMs, exhibited reduced flexural strengths.

The consistent decrease in FS with increasing RHA content, to the point where D6 and D7 fall below the control, is a notable observation. This contrasts with the compressive strength results, where RHA at 10% (D5) showed significant improvement. This divergence highlights that the factors affecting FS can differ from those influencing compression. FS is susceptible to defects, porosity, and degradation of the matrix integrity. The porous nature of RHA particles reduces the amount of free water available for cement hydration, resulting in increased porosity. This observation aligns with research by Khan et al. [48], who also noted that RHA increases the water demand in mixes, adversely affecting strength due to insufficient water for hydration.

In ternary blends, the adverse effect of higher RHA content (above 15%) on flexural strength becomes even more significant, especially in mixes with very high overall SCM percentages (D21–D23). This indicates a dilution effect of Portland cement, combined with the detrimental influence of excessive porosity in RHA. Although GGBS usually improves strength, its beneficial effects are reduced when RHA's negative impacts on water demand and porosity dominate at higher replacement levels, resulting in a less ductile matrix.

4.3.2. Flexural strength of binary and ternary blends with Ultrafine GGBS

Fig. 14 presents the 28-day FS results for mixes incorporating Ultrafine GGBS (UG) and RHA.

- **Binary UGGBS Blend:** Substituting cement with 10% UGGBS (Mix D8) tremendously enhanced the flexural strength.
- **Ternary Blends (UG & RHA):** Mix D13, containing 10% UG and 15% RHA, reportedly yielded the best strength among all ternary mixes. However, the text notes that higher substitution levels with RHA had an adverse impact on FS, similar to the observations for compressive strength.

The substantial enhancement in flexural strength with the inclusion of Ultrafine GGBS (UG) (Mix D8) is a key finding that reinforces its benefits. The ultrafine particles of GGBS, as highlighted in previous discussions, contribute significantly to pore filling and refinement within the mortar matrix. This micro-filler effect densifies the material, reduces overall porosity,

and improves the homogeneity and integrity of the cement paste. Moreover, the increased surface area of UG particles enhances pozzolanic reactions, leading to the formation of a denser and stronger C-S-H gel structure. This improved microstructure not only enhances compressive strength but also boosts tensile capacity and, consequently, flexural strength by providing a more continuous and robust load-bearing network. This aligns with a broad body of research demonstrating that ultrafine SCMs can significantly improve the mechanical properties of cementitious composites due to their better particle packing.

Overall, it was observed that Mix D13 (10% UG, 15% RHA) achieved the best strength among the ternary blends. This suggests that the profound positive impact of UG can mitigate the adverse effects of RHA, even at a 15% replacement level. The dense packing and enhanced hydration facilitated by UG likely compensate for some of the porosity introduced by RHA. However, even with UG's benefits, excessive RHA leads to higher water demand and increased porosity, which ultimately impacts the mortar's mechanical performance.

4.3.3. Flexural strength of quaternary blends (Cement, GGBS, UGGBS, RHA)

Fig. 15 presents the 28-day FS results for mixes incorporating a quaternary blend of cement, GGBS, UGGBS, and RHA.

- **Effect of RHA in Quaternary Blends:** The results indicate that partially replacing cement with RHA generally decreased the FS in quaternary blends. Specifically, mixes D24 (G20 UG10 R10), D27 (G25 UG10 R10), and D30 (G30 UG10 R10) reportedly showed slightly lower FS than the control mix (D1), despite the presence of beneficial GGBS and UGGBS. This contrasts sharply with their compressive strengths, where D24 and D27 were significantly higher than the control.
- **Quaternary Blends without RHA:** In contrast, mixes D9 (G20 UG10 R0), D10 (G25 UG10 R0), and D11 (G30 UG10 R0), which contained GGBS and UGGBS but no RHA, showed better performance than the D1 control mix.

The results from the quaternary blends reveal a complex interplay between the different SCMs, particularly with respect to FS. The superior performance of mixes D9, D10, and D11 (without RHA) highlights the strong synergistic contribution of combining GGBS and UGGBS to FS, similar to their impact on CS. This confirms that a blend of GGBS and UGGBS effectively densifies the matrix and enhances the overall strength properties. However, the consistently lower flexural strength of quaternary mixes containing RHA (D24,

D27, D30), even at a 10% RHA replacement level, suggests a greater sensitivity of flexural performance to the presence of RHA compared to compressive strength. Further research could explore the use of advanced superplasticizers to reduce water demand in RHA-based mixes or evaluate the impact of ultrafine RHA on mitigating these adverse effects on flexural performance in multi-component binder systems.

5. Conclusion

This study investigated the combined use of agro-industrial and industrial by-products, specifically RHA, GGBS, and UGGBS, as partial replacements for cement in mortar systems. A total of 32 mixes were evaluated for flowability, CS, and FS over 28 days, providing new insights into the compatibility and synergistic effects of multi-SCM systems.

- All mortar mixes met the target flow of 200 ± 20 mm. However, as RHA content increased beyond 10%, there was a notable rise in water and superplasticizer demand due to its high surface area and water absorption. This effect was particularly pronounced in ternary and quaternary blends, highlighting the critical role of mix optimization when incorporating highly porous agro-waste.
- Mixes incorporating GGBS and RHA showed that increased binder substitution generally led to reduced strength, yet several combinations still outperformed the control mix. Notably, mixes with 20-30% GGBS and 10-15% RHA maintained strength levels suitable for structural applications, demonstrating their viability as sustainable alternatives. The inclusion of UGGBS significantly enhanced compressive strength, confirming its high reactivity and beneficial contribution to blended systems. However, when combined with higher RHA content, the positive effects were diminished, suggesting the need for careful proportioning to maintain performance.
- Quaternary mixes revealed that up to 10% RHA, 10% UGGBS, and 20-25% GGBS can be used synergistically without compromising mechanical performance. A similar trend was observed in FS development, reinforcing the suitability of these blends for practical applications.
- Overall, the findings highlight a novel combination of industrial and agro-waste materials that can be effectively used to design eco-efficient mortars. The results demonstrate that UGGBS serves as a performance-enhancing SCM, while controlled RHA incorporation offers a sustainable solution provided its mix design challenges are addressed. This study contributes to the broader

understanding of multi-SCM systems and provides actionable data for developing sustainable, high-performance cementitious materials suitable for real-world applications.

The results of this study demonstrate that by carefully optimizing blend proportions and controlling the particle size distribution of supplementary cementitious materials, the proposed cementitious mixtures can be effectively applied in construction while maintaining structural integrity. These findings provide a valuable foundation for designing more sustainable and performance-oriented mortar systems.

6. Recommendations

Future research should investigate the long-term durability, microstructural evolution, and shrinkage behavior of these hybrid systems to realize their potential in practical applications. Furthermore, this study lays the groundwork for developing mixtures tailored for advanced construction technologies. In particular, the authors intend to extend this research towards formulating and evaluating these blends for 3D concrete printing. The enhanced understanding of flowability and strength characteristics gained here will guide the optimization of mix designs specifically suited for digital construction and layer-by-layer extrusion processes.

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Conflict of interest

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Data availability statement

All graphs and data obtained or generated during the investigation appear in the published article.

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Author contributions

Devansh Goel: Conceptualization, methodology, validation, formal analysis, investigation, visualization, writing - original draft.

Sudarshan D. Kore: Methodology, Writing - Review and Editing, Supervision.

Ethics

There are no ethical issues with the publication of this manuscript.

Dataset

All graphs and data obtained or generated during the investigation appear in the manuscript.

Abbreviations

SCMs:	Supplementary Cementitious Materials
OPC:	Ordinary Portland Cement
GGBS or G:	Ground Granulated Blast-Furnace Slag
UGGBS or UG:	Ultrafine Ground Granulated Blast-Furnace Slag
RHA or R:	Rice Husk Ash
PCE:	Poly-Carboxylate Ether
SEM:	Scanning Electron Microscope
ITZ:	Interfacial Transition Zone
C-S-H:	Calcium Silicate Hydrate
CH:	Calcium Hydroxide
w/b:	Water to binder ratio
CS:	Compressive Strength
FS:	Flexural Strength

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