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Enhanced compressive strength and durability of low-molarity alkali-activated concrete with recycled aggregates: An experimental and response surface methodology approach

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Abstract

The construction industry faces increasing challenges related to environmental impact, including high carbon emissions from Portland cement production and the management of construction and demolition waste. This study addresses these issues by developing sustainable alkali-activated concrete (AAC) using low-molarity (2M) activators, incorporating fly ash and ground granulated blast furnace slag (GGBS) as binders, and exploring the use of recycled coarse aggregates (RCA) as a replacement for natural aggregates (CA). The objective was to evaluate the influence of varying sodium silicate-to-sodium hydroxide (SS:SH) ratios on the compressive strength properties, durability, and sustainability of AAC. Nine mixes were designed with SS:SH ratios ranging from 1.5 to 3.5, incorporating both CA and RCA in varying proportions. Compressive strength, water absorption, and sulphate resistance were assessed, with specific emphasis on the role of SS:SH ratio in mitigating the weaknesses of RCA. Response surface methodology (RSM) with central composite design (CCD) was also employed to analyse the combined effects of the SS:SH ratio (1.5 to 3.5) and RCA content (0% to 100%). Experimental results revealed that higher SS:SH ratios significantly improved performance. M3 (SS:SH = 3.5, 100% CA) achieved the highest compressive strength of 34 MPa, superior impact resistance, and excellent sulphate resistance with a residual strength retention of 92 percent. RCA mixes, while exhibiting higher porosity and reduced initial performance, showed substantial improvements with optimized SS:SH ratios. M9 (SS:SH = 3.5, 100% RCA) demonstrated balanced properties, achieving a compressive strength of 28 MPa and retaining 87 percent of its strength under sulphate exposure. The optimal mix identified through RSM CCD consists of an SS:SH ratio of 3.32 and 48.6% RCA. This mix achieved the best balance between sustainability and performance, demonstrating compressive strengths above 30.09 MPa, residual sulphate strength retention of 85.51%, and superior impact resistance, water absorption, and durability. The study highlights the critical role of SS:SH ratio in enhancing matrix densification, mitigating the limitations of RCA, and ensuring the durability of low-molarity systems. These findings promote the application of alkali-activated concrete in sustainable construction, enabling the integration of RCA in structural elements without compromising performance or durability.

Keywords: AAC, SS: SH ratio, RCA, low molarity, impact resistance, sulfate resistance and sustainable construction.

Introduction

The construction industry is a vital contributor to global infrastructure development, playing a pivotal role in modern societies. However, it is also one of the largest contributors to environmental degradation, accounting for significant energy consumption and greenhouse gas emissions. Traditional Portland cement-based concrete, the backbone of construction, is a key driver of these environmental issues due to its energy-intensive manufacturing process and substantial carbon dioxide emissions [1], [2]. These challenges underscore the urgent need for alternative, sustainable construction materials that can reduce the industry ecological footprint without compromising performance. Alkali-activated materials (AAMs), which utilize industrial by-products like fly ash and GGBS, have emerged as a promising solution to these pressing concerns [3], [4].

Fly ash and GGBS are abundant by-products of the coal power and steel industries, respectively, often relegated to landfills, contributing to environmental pollution [5], [6], [7]. Harnessing these materials in the production of high-performance concrete not only addresses waste management challenges but also significantly reduces the reliance on Portland cement[8]. Alkali-activated systems leverage the pozzolanic and latent hydraulic properties of these by-products, enabling the production of concrete with enhanced mechanical and durability properties [9], [10], [11]. By replacing conventional cement binders, these systems reduce the carbon footprint of construction materials while promoting the principles of a circular economy [11], [12].

In parallel with these advancements, there is a growing interest in the utilization of RCA derived from construction and demolition waste. The generation of such waste is inevitable during infrastructure development and renovation, and its improper disposal poses severe environmental challenges. Incorporating RCA into concrete production offers dual benefits: it reduces the need for natural coarse aggregates, whose excessive extraction depletes finite resources, and mitigates the environmental burden associated with landfilling construction waste [13], [14], [15]. RCA also aligns with the principles of sustainability and resource conservation by creating a circular pathway in which waste becomes a valuable input. While RCA can influence certain mechanical properties of concrete, effective mix design and processing methods can mitigate these effects, ensuring a balance between environmental benefits and structural performance. As such, integrating RCA into alkali-activated concrete systems holds immense potential to further reduce the construction industry ecological footprint [16].

Another crucial consideration in the pursuit of sustainable construction is the use of low-molarity alkali-activated binders. Traditional alkali-activated systems often rely on highly concentrated alkali solutions, particularly sodium hydroxide, to facilitate geopolymerization. However, the use of high-molarity solutions presents challenges such as increased production costs, elevated energy demands, and greater risks in handling due to their caustic nature. These issues can offset the environmental and economic benefits of alkali-activated materials. Low-molarity systems address these concerns by minimizing alkali concentration while maintaining sufficient reactivity to produce concrete with desirable mechanical and durability properties [17]. This not only improves safety and cost-efficiency but also expands the feasibility of using alkali-activated binders in large-scale construction applications. Furthermore, low-molarity systems reduce the environmental impact associated with activator production, making them an essential innovation in the development of eco-friendly construction materials [18].

For structural applications, combining recycled coarse aggregate and low-molarity alkali-activated binders presents a holistic approach to addressing sustainability challenges. While RCA promotes waste recycling and reduces reliance on natural resources, low-molarity systems enhance the overall environmental and economic viability of alkali-activated concrete [19]. Together, these innovations advance the development of durable, high-performance materials that meet the demands of modern infrastructure while aligning with global sustainability goals [20]. This study aims to explore the synergy between these components, providing a comprehensive perspective on how their integration can unlock the full potential of sustainable construction technologies.

In addition to compressive strength, which is a primary indicator of structural performance, properties such as impact resistance and durability are critical for the long-term functionality and resilience of concrete. Similarly, durability, characterized by resistance to aggressive environmental conditions such as sulfate attack, freeze-thaw cycles, and chloride ingress, ensures the material ability to retain its performance over extended periods. The interplay of these mechanical and durability properties is particularly significant in sustainable concrete systems, where the integration of recycled aggregates introduces additional challenges related to porosity and bond strength. Therefore, optimizing these parameters in alkali-activated concrete is vital for achieving high-performance, sustainable solutions for modern construction demands.

Response Surface Methodology (RSM) is at the core of this innovative approach. Unlike traditional trial-and-error methods [21], [22], RSM offers a robust framework for systematically exploring and understanding the intricate relationships between variables in alkali-activated systems. Variables such as the proportions of fly ash and GGBS, the concentration of the alkali activator, the curing temperature, and the curing duration are not only interconnected but also significantly influence the mechanical and durability properties of the resulting concrete. By employing RSM, this study models these complex interactions, enabling the identification of optimal combinations that maximize performance outcomes while maintaining material sustainability. For instance, while increasing alkali concentration might improve strength, it could simultaneously impact workability or durability negatively. Similarly, the ratio of fly ash to GGBS might have different implications for impact resistance compared to resistance to chloride penetration. RSM makes it possible to navigate these trade-offs effectively, providing a comprehensive map of the material performance landscape [23]. This facilitates the development of mix designs that strike an ideal balance between competing requirements, such as strength, durability, and sustainability. Furthermore, the application of RSM in this study extends beyond simple optimization. By generating predictive models, RSM enables researchers to extrapolate findings and predict the performance of concrete mixes outside the experimentally tested range [24]. This capability is particularly valuable for scaling up the findings to real-world applications, where construction conditions and material availability may vary. The insights gained from this process not only inform material selection and design but also reduce the need for extensive trial-based testing, saving both time and resources [25].

In addition to addressing environmental and performance challenges, this study emphasizes the life-cycle benefits of alkali-activated concrete systems. Materials with high impact resistance and durability contribute to the longevity of structures, reducing the frequency of repairs and replacements. This not only lowers material and labour costs but also decreases the embodied carbon associated with reconstruction activities. As modern construction increasingly focuses on resilience and sustainability, alkali-activated systems provide an avenue for achieving these objectives without sacrificing performance. In summary, this study aims to advance the development of high-performance sustainable concrete through the incorporation of fly ash and GGBS as alkali-activated binders. By evaluating impact resistance and durability using experimental techniques and optimizing the material properties through RSM, this research addresses critical gaps in knowledge and application. The findings are expected to contribute to the development of resilient, eco-friendly construction materials that align with the goals of modern sustainable infrastructure.

Experimental methodology

Materials

The materials used in this study were carefully selected to develop high-performance sustainable concrete incorporating fly ash and GGBS as alkali-activated binders. These materials were combined with alkali activators, fine and coarse aggregates, water, and superplasticizers to achieve the desired workability, strength, and durability. The properties and roles of each material are elaborated below.

Fly ash, a by-product of coal combustion in thermal power plants, was utilized as one of the primary binders. Class F fly ash, characterized by its low calcium content, was chosen for its superior pozzolanic properties, which promote geopolymerization when activated with alkali solutions. The specific gravity of the fly ash ranged between 2.2 and 2.4, and its fineness, measured using Blaine's specific surface area, was in the range of 300 to 400 m²/kg. Chemically, the fly ash was rich in silica ($SiO_2 > 50\%$) and alumina (Al_2O_3 ~25%), with low lime content ($CaO < 10\%$). This chemical composition plays a critical role in the formation of aluminosilicate gel, which enhances the long-term mechanical properties and durability of the concrete. Fly ash also contributes to sustainability by repurposing industrial waste and reducing the reliance on Portland cement.

GGBS is another industrial by-product, was sourced from a local steel plant. Known for its latent hydraulic properties, GGBS reacts with alkali activators to provide rapid strength development and improve the microstructure of the concrete. The specific gravity of GGBS was found to be between 2.9 and 3.0, with a Blaine fineness of 400–450 m²/kg. Its chemical composition includes a high proportion of calcium oxide (CaO ~40%), silica (SiO_2 ~30%), and alumina (Al_2O_3 ~15%), which are essential for hydration and geopolymerization reactions. The inclusion of GGBS not only enhances the mechanical properties of the mix but also increases its resistance to sulfate and chloride attack, thereby improving its durability.

Alkali activators, comprising a combination of sodium silicate and sodium hydroxide, were employed to initiate the geopolymerization process. Sodium silicate, with a silica-to-sodium oxide ($SiO_2:Na_2O$) ratio of approximately 2.5 and a specific gravity of 1.5, served as the primary activator, providing the necessary silicate ions for the formation of the geopolymer gel. Sodium hydroxide, used in pellet form and dissolved in water to prepare an 8M solution, acted as a secondary activator, facilitating the dissolution of aluminosilicates present in fly ash and GGBS. The strong alkalinity of sodium hydroxide (pH ~14) ensures efficient activation and gel formation. Together, these activators play a crucial role in achieving the high strength and durability of alkali-activated concrete.

Fine aggregates in the form of natural river sand were used to ensure good workability and to minimize voids in the mix. The sand had a specific gravity of 2.6–2.7, a fineness modulus of 2.6, and a maximum particle size of 4.75 mm, as specified in IS 383:2016. These properties made the sand suitable for producing a dense concrete matrix with reduced permeability. Coarse aggregates, consisting of crushed granite stones with a maximum size of 16 mm, were incorporated to provide bulk and strength to the concrete. The specific gravity of the coarse aggregate ranged between 2.6 and 2.8, ensuring compatibility with the binder matrix. Additionally, RCA is derived from crushed concrete waste sourced from construction and demolition activities, was used as a partial or complete replacement for natural coarse aggregates. The RCA had a specific gravity of 2.4–2.5, slightly lower than that of natural aggregates, due to the presence of adhered mortar and voids. It also exhibited a higher water absorption capacity of 3–6%, reflecting its porous nature.

Water was used both to dissolve the sodium hydroxide pellets and to facilitate the mixing of the concrete. Only potable water free from impurities was used to prevent any adverse chemical reactions that could affect the concrete performance.

The water-to-binder ratio was maintained between 0.3 and 0.4, striking a balance between workability and mechanical strength. Additionally, a polycarboxylate ether (PCE)-based superplasticizer was added at a dosage of 0.5–1.0% by weight of the binder to enhance the workability of the mix without compromising its strength. The use of superplasticizers ensured uniform dispersion of the binder particles, particularly in low water-to-binder ratio mixes, which are critical for high-performance concrete.

Mix design

This study focused on developing high-performance sustainable concrete by utilizing fly ash and GGBS as alkali-activated binders. A total of nine mixes (Table 1) were designed and cast to investigate the effects of variations in sodium hydroxide molarity, sodium silicate-to-sodium hydroxide (SS:SH) ratios, and aggregate type on the mechanical and durability properties.

Table 1 Mix proportion of concrete.

Mix ID	Fly Ash (kg/m3)	GGBS (kg/m3)	FA (kg/m3)	CA (kg/m3)	RCA (kg/m3)	SH (kg/m3)	SS (kg/m3)	SP (kg/m3)	SS:SH Ratio
M1	160	240	680	1200	-	96	64	2.5	1.5
M2	160	240	680	1200	-	114.29	45.71	2.5	2.5
M3	160	240	680	1200	-	124.8	35.2	2.5	3.5
M4	160	240	680	600	600	96	64	2.5	1.5
M5	160	240	680	600	600	114.29	45.71	2.5	2.5
M6	160	240	680	600	600	124.8	35.2	2.5	3.5
M7	160	240	680	-	1200	96	64	2.5	1.5
M8	160	240	680	-	1200	114.29	45.71	2.5	2.5
M9	160	240	680	-	1200	124.8	35.2	2.5	3.5

The mix design followed a fixed fly ash-to-GGBS ratio of 40:60, with a total binder content of 400 kg/m³. The FA content was kept constant at 680 kg/m³, while the CA and RCA were varied across three configurations: 100% CA, 50% CA + 50% RCA, and 100% RCA. The maximum aggregate size was limited to 16 mm to improve packing density and reduce void content, as per IS 383:2016 specifications. The alkali activator solution consisted of SS and SH, with variations in SS:SH ratios of 1.5, 2.5, and 3.5. Sodium hydroxide molarity was fixed at 2M to evaluate the effect of activator concentration. The activator solution-to-binder ratio was maintained at 0.4. The total activator solution was divided between SS and SH according to the SS:SH ratio, as shown in the table below. A polycarboxylate ether-based superplasticizer was used at 2.5 kg/m³ to enhance workability.

Casting and Curing

The casting process involved a systematic and meticulous approach to ensure uniformity, consistency, and quality of the high-performance sustainable concrete specimens. The materials, including FA, CA and RCA, fly ash, GGBS, and alkali activators, were prepared and weighed according to the mix proportions. The process began with the dry mixing of fine aggregates, such as natural river sand, CA and RCA, which consisted of crushed granite stones with a maximum size of 16 mm. This step ensured an even distribution of particles, reducing the likelihood of segregation in the final mix. Following this, the alkali-activated binders fly ash and GGBS were added to the aggregate blend. The binders were thoroughly mixed to achieve a homogeneous dry mixture before the addition of the alkali activator solution.

The alkali activator solution was prepared by dissolving sodium hydroxide (NaOH) pellets in potable water to create an 8M solution. This solution was allowed to cool and stabilize for 24 hours prior to mixing. Sodium silicate (Na_2SiO_3) was then added to the sodium hydroxide solution at the required ratio, forming the combined alkali activator. The activator solution was gradually introduced into the dry mixture while continuously stirring to ensure proper coating of the binder and aggregates. To enhance workability and reduce the water content, a polycarboxylate ether (PCE)-based superplasticizer was added in the range of 0.5–1.0% of the binder's weight. The water-to-binder ratio was carefully maintained between 0.3 and 0.4, ensuring an optimal balance between strength and workability. The mixing process continued until the concrete achieved a uniform and cohesive consistency, free from lumps or segregation.

Once the concrete mix was prepared, it was poured into moulds to cast specimens for various tests. The moulds were selected based on the type of tests to be conducted. For compressive strength evaluation, moulds with dimensions of **150 mm × 150 mm × 150 mm** were used to prepare cube specimens. For impact resistance tests, disc-shaped specimens with a diameter of **150 mm** and a height of **63.5 mm** were cast. Each mould was carefully filled in layers, and a table vibrator was employed during the filling process to eliminate entrapped air and ensure a dense, compact concrete matrix. The surface of the moulds was levelled and smoothed to achieve a uniform finish, enhancing the accuracy of subsequent testing.

After the casting process, the specimens were covered with a plastic sheet to prevent moisture loss and allow the initial setting process to proceed under controlled conditions. The moulds were demoulded after 24 hours, and the specimens were transferred to a curing environment designed to replicate practical conditions. The curing environment was maintained at a controlled **room temperature of approximately 25°C** with a **relative humidity of 60–70%,** creating ideal conditions for the geopolymerization and hydration reactions of the alkali-activated binders. Ambient curing was selected as the primary curing method to align with real-world applications, where elevated temperature curing may not always be feasible. This method is particularly effective for concrete mixes with a higher content of GGBS, as the slag component exhibits self-cementing properties under ambient conditions. The specimens remained in this curing environment until the designated testing dates, allowing sufficient time for the chemical reactions to progress and for the concrete to develop its desired mechanical and durability properties. The curing process played a crucial role in ensuring the long-term performance of the concrete by enhancing its resistance to environmental stresses, improving its impact resistance, and reducing its susceptibility to degradation. By combining a carefully executed casting process with a tailored ambient curing regime, this study ensured that the specimens achieved their full potential in terms of mechanical strength, durability, and sustainability. The systematic approach to casting and curing forms the foundation for reliable and reproducible evaluation of the high-performance sustainable concrete developed in this research.

Testing Procedure

Compressive strength

The compressive strength of the concrete was measured using cube specimens with dimensions of 150 mm × 150 mm × 150 mm. These specimens were cast and cured according to the standard procedure, and the tests were conducted as per ASTM C39/C39M standards [26], [27], [28]. Each specimen was subjected to uniaxial compression using a universal testing machine with a load capacity of 2000 kN. The loading rate was maintained at 0.25 MPa/s to ensure consistent and reliable results. The compressive strength was calculated by dividing the maximum load by the cross-sectional area of the specimen [29], [30]. For each mix, three specimens were tested at 7 and 28 days of curing, and the average compressive strength was reported. This test provided valuable data on the load-bearing capacity of the concrete, which is crucial for structural applications.

Durability test

To evaluate the durability of concrete incorporating RCA, two key tests were conducted: the water absorption test and the sulphate attack test. These tests were designed to assess the porosity, permeability, and resistance of the concrete to aggressive environments, providing insights into its long-term performance. Additionally, the compressive strength of cubes exposed to sulphate attack was measured to determine the residual mechanical performance.

The water absorption test was performed according to ASTM C642 to evaluate the porosity and permeability of the concrete [2]. Concrete specimens were oven-dried to a constant weight, and their dry weight (Wd) was recorded. These specimens were then immersed in water at room temperature for 24 hours to allow full absorption. After immersion, the specimens were surface-dried with a cloth, and their saturated weight (Ws) was recorded. The percentage water absorption was calculated using the formula:

$$\text{Water Absorption (\%)} = \left(\frac{\text{Ws} - \text{Wd}}{\text{Wd}}\right) \text{x } 100 \qquad - \qquad (1)$$

where Wd is the oven-dry weight (in grams), and Ws is the saturated weight after immersion (in grams). Lower water absorption values indicate denser concrete with reduced permeability. This test is particularly critical for RCA-based concrete, as RCA tends to increase water absorption due to its porous structure and adhered mortar.

The sulphate attack test was conducted in accordance with ASTM C1012 to assess the concrete's resistance to sulphate-induced deterioration. Cube specimens were cast, cured for 28 days, and then submerged in a 5% sodium sulphate (Na_2SO_4) solution for a prolonged period. The solution was refreshed regularly to maintain its concentration. Specimens were visually inspected periodically for signs of surface deterioration, cracking, or spalling caused by the sulphate solution.

The resistance of the concrete to sulphate attack was assessed through two metrics: percentage weight change and residual compressive strength. The weight of the specimens before (Wi) and after (Wf) immersion in the sulphate solution was recorded, and the percentage weight change was calculated as follows:

$$\text{Weight Change (\%)} = \left(\frac{\text{Wf} - \text{Wi}}{\text{Wi}}\right) \text{x } 100 \qquad - \qquad (2)$$

where Wi is the initial weight before immersion (in grams), and Wf is the final weight after immersion (in grams). A smaller weight loss indicates better sulphate resistance.

The compressive strength of the cubes was also measured after exposure to sulphate attack to determine the residual compressive strength and evaluate the structural integrity of the concrete. The compressive strength test was conducted on the sulphate-exposed cubes using a universal testing machine, and the results were compared with the compressive strength of unexposed control cubes. The residual strength percentage was calculated as:

$$\text{Residual Strength } (\%) = \left(\frac{\text{Compressive Strength of Exposed Cubes}}{\text{Compressive Strength of Control Cubes}}\right) \text{x } 100 \qquad - \qquad (3)$$

Response surface methodology

RSM was employed to optimize the experimental design and analyse the effects of key mix design parameters on the concrete's performance. A Central Composite Design (CCD) was used to systematically vary the proportions of fly ash, GGBS, alkali activators, and water-to-binder ratios. CCD includes factorial points, axial points, and central points, allowing for a robust exploration of the experimental space. Key factors such as the fly ash-to-GGBS ratio, alkali activator concentration, sodium silicate-to-sodium hydroxide ratio, and water-to-binder ratio were chosen as independent variables. The responses included compressive strength and durability parameters. A total of 30 experimental runs were generated using CCD, covering low, medium, and high levels of each factor. The results from the compressive strength and durability tests were input into the RSM model to establish mathematical relationships between the input parameters and the output properties. The RSM model provided response surfaces and contour plots, illustrating the effects of individual parameters and their interactions. Optimization was performed to maximize compressive strength and impact resistance while minimizing water absorption and chloride permeability. This approach enabled the development of a mix design with a balance of mechanical and durability properties.

Results and discussion

Compressive strength

The compressive strength results revealed significant trends influenced by the SS:SH ratio, the type of coarse aggregate, and the use of low-molarity alkali activators at 2M concentration. This study intentionally used a low molarity system to reduce environmental and safety concerns typically associated with highly alkaline activators. Despite this, the compressive strength results demonstrated that the designed mixes achieved satisfactory performance, showcasing the potential of sustainable low-molarity systems for concrete applications.

The results underline the importance of CA in contributing to the compressive strength of concrete. Mixes with CA consistently outperformed those with RCA due to the superior density and bonding quality of natural aggregates. Among the CA mixes, M3, which had the highest SS:SH ratio of 3.5, achieved the highest 28-day compressive strength of 34 MPa. This value represents a **21.4% increase** compared to M1, which had a lower SS:SH ratio of 1.5, and a **9.7% increase** compared to M2, which had a moderate SS:SH ratio of 2.5. The improvement in strength with increasing SS:SH ratio can be attributed to the higher availability of silicate ions at higher ratios. These silicate ions enhance the geopolymerization process, forming a denser geopolymer gel matrix that strengthens the bond between the aggregate and binder and minimizes microstructural flaws.

The impact of the SS:SH ratio on the strength development was also evident from the 7-day strength results. M3 achieved 22 MPa after 7 days, which is **22.2% higher** than M1 (18 MPa) and **10% higher** than M2 (20 MPa). The faster rate of strength gain in M3 highlights the accelerated geopolymerization kinetics facilitated by higher silicate ion availability. In contrast, RCA-based mixes showed a reduction in compressive strength due to the inherent porous nature of RCA, which reduces the aggregate-binder bond strength and increases microstructural voids. M7, with a lower SS:SH ratio of 1.5 and 100% RCA, recorded the lowest 28-day compressive strength of 24 MPa. This is **14.3% lower** than M4, which used 50% RCA and achieved 26 MPa, and **31.6% lower** than M1, which used 100% CA and achieved 28 MPa. These reductions can be attributed to the adhered mortar and increased water absorption of RCA, which compromise the structural integrity of the concrete matrix.

However, the SS:SH ratio demonstrated a mitigating effect on the performance of RCA-based mixes. For instance, M9, which also used 100% RCA but had a higher SS:SH ratio of 3.5, achieved a 28-day compressive strength of 28 MPa. This represents a **16.7% improvement** compared to M7, demonstrating the critical role of the SS:SH ratio in enhancing the performance of RCA mixes. The increase in silicate content contributed to improved geopolymer gel formation, filling the microstructural voids created by the porous RCA and enhancing the overall matrix density.

The results (Fig. 1) also highlighted that while RCA mixes generally showed lower strength compared to CA mixes, optimizing the SS:SH ratio helped narrow the gap. For instance, the strength difference between M3 (34 MPa) and M9 (28 MPa) was only **17.6%**, whereas the difference between M1 (28 MPa) and M7 (24 MPa) was **14.3%**, indicating that higher SS:SH ratios reduced the relative performance disparity between CA and RCA mixes. The findings from this study highlight the potential of low-molarity alkali-activated systems in achieving desirable compressive strength when combined with optimal SS:SH ratios. Furthermore, the study demonstrates that RCA can be effectively utilized in sustainable concrete applications, provided the mix design compensates for its inherent weaknesses through a higher

SS:SH ratio. These results emphasize the need for careful optimization of the binder composition to achieve both sustainability and performance in structural concrete.

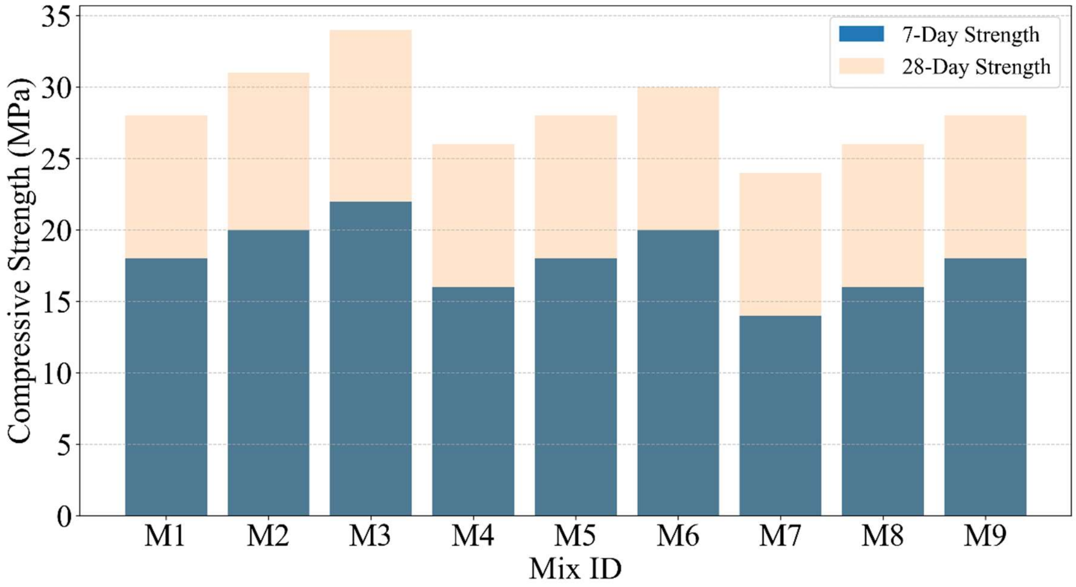

Figure 1 7 Days and 28 days compressive strength of concrete.

Water absorption

Water absorption is a crucial parameter for assessing the porosity and permeability of concrete, which directly influence its durability and resistance to aggressive environments. The results (Fig. 2) highlight significant differences between mixes with natural coarse aggregates and recycled coarse aggregates, as well as the impact of the SS:SH ratio on reducing water absorption.

Performance of natural aggregate mixes

Mixes incorporating natural coarse aggregates exhibited significantly lower water absorption values compared to recycled aggregate mixes, reflecting their denser and more cohesive microstructure. Among these, M3, which had the highest SS:SH ratio of 3.5, recorded the lowest water absorption value of 2.1 percent. This was 16 percent lower than M1, which had a lower SS:SH ratio of 1.5 and recorded a value of 2.5 percent, and 8.7 percent lower than M2, which had a moderate SS:SH ratio of 2.5 and recorded a value of 2.3 percent.

The reduction in water absorption with an increasing SS:SH ratio can be attributed to the enhanced geopolymerization process at higher silicate concentrations. A higher SS:SH ratio increases the availability of silicate ions, which promotes the formation of a dense and compact geopolymer gel. This densification reduces the number of interconnected pores in the matrix, thereby limiting the ingress of water. Additionally, the strong bond between the natural aggregates and the binder at higher SS:SH ratios further minimize microstructural voids and enhances the overall impermeability of the mix.

Challenges with recycled aggregate mixes

Recycled aggregate mixes exhibited higher water absorption values due to the inherent porous nature of recycled aggregates and the adhered mortar on their surface. The presence of residual cement pastes and micro-cracks in recycled aggregates increases the number of capillary pores, making the concrete more permeable to water. Among the recycled aggregate mixes, M7, which had a low SS:SH ratio of 1.5 and 100 percent recycled aggregates, recorded the highest water absorption value of 3.2 percent. This value was 28 percent higher than M4, which incorporated 50 percent recycled aggregates and recorded a value of 3.0 percent, and 28 percent higher than M1, which used 100 percent natural aggregates and recorded a value of 2.5 percent.

The high-water absorption in M7 underscores the combined impact of recycled aggregates' porous structure and the insufficient silicate ion availability at low SS:SH ratios. The weak bonding between recycled aggregates and the binder, coupled with the high-water absorption of the adhered mortar, creates a microstructure that is prone to water ingress and permeability.

Effect of SS:SH Ratio on RCA Mixes

The SS:SH ratio played a critical role in mitigating the high-water absorption of recycled aggregate mixes. As the SS:SH ratio increased, the availability of silicate ions improved, leading to better geopolymer gel formation and a more compact matrix. For instance, M9, which had an SS:SH ratio of 3.5 and 100 percent recycled aggregates, recorded a water absorption value of 2.8 percent. This represents a 12.5 percent reduction compared to M7, which had a lower SS:SH ratio of 1.5 and recorded a value of 3.2 percent.

The improved performance of M9 can be attributed to the densification of the binder matrix, which fills the voids and capillary pores present in recycled aggregates. Additionally, the higher SS:SH ratio enhances the interfacial transition zone between the recycled aggregates and the binder, reducing water penetration at the aggregate-binder interface. These improvements highlight the effectiveness of a higher SS:SH ratio in addressing the inherent weaknesses of recycled aggregates in terms of water absorption.

Observations

1. The results show that increasing the SS:SH ratio consistently reduced water absorption across all mixes. The higher availability of silicate ions at elevated SS:SH ratios improved the geopolymerization process, leading to a denser matrix with fewer interconnected pores. This effect was observed in both natural and recycled aggregate mixes, demonstrating the versatility of this approach.
2. Natural aggregate mixes exhibited superior performance, with significantly lower water absorption values compared to recycled aggregate mixes. The dense and cohesive microstructure of natural aggregates, combined with their strong bond with the binder, minimized permeability. However, recycled aggregate mixes showed notable improvements at higher SS:SH ratios, narrowing the performance gap between natural and recycled aggregates.
3. The porous nature of recycled aggregates and the adhered mortar contributed to higher water absorption in recycled aggregate mixes. However, increasing the SS:SH ratio effectively mitigated these challenges by densifying the binder matrix and improving the interfacial transition zone between recycled aggregates and the binder.
4. Mix M3 with natural aggregates and an SS:SH ratio of 3.5, emerged as the best-performing mix, achieving the lowest water absorption value of 2.1 percent. Among recycled aggregate mixes, M9, with 100 percent recycled aggregates and an SS:SH ratio of 3.5, demonstrated the most balanced performance, achieving a 12.5 percent reduction in water absorption compared to M7, making it a viable option for sustainable construction applications.

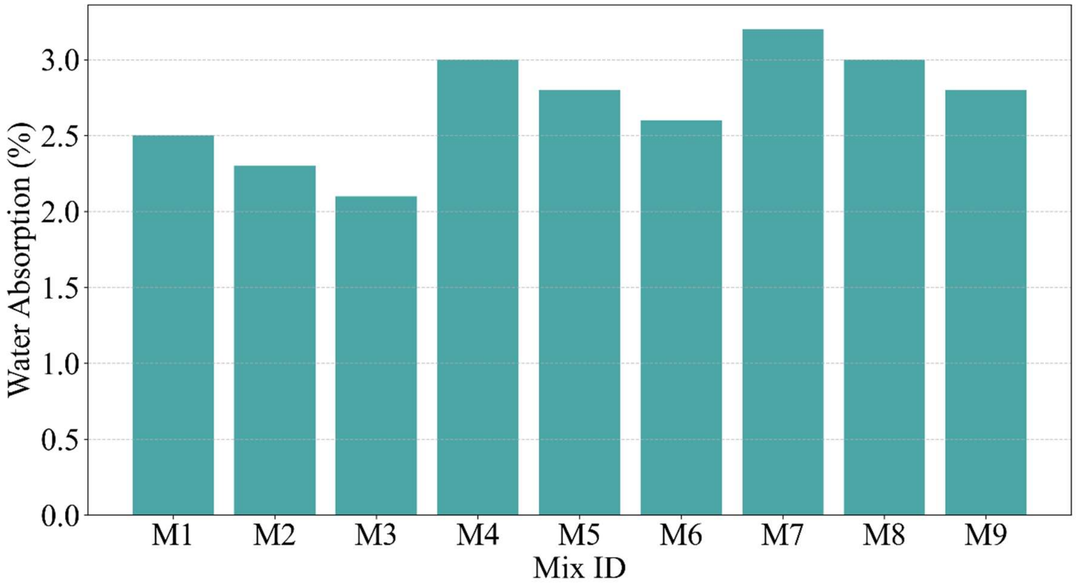

Figure 2 Water absorption (%) of low molarity alkali activated concrete.

Sulphate resistance

The sulphate attack test, assessed through weight change and residual compressive strength, provides critical insights into the durability of concrete mixes under aggressive sulphate-rich environments. The results demonstrate distinct differences between CA and RCA mixes, as well as the significant role of the SS:SH ratio in mitigating sulphate-induced deterioration.

Weight Change Under Sulfate Attack

The weight change results (Fig. 3) reveal the ability of the mixes to resist sulphate ion ingress and the associated chemical reactions. Natural CA mixes exhibited superior sulphate resistance due to their denser matrix and lower porosity, which restricted the penetration of sulphate ions. Among these, M3, with the highest SS:SH ratio of 3.5, recorded the lowest weight change of 1.0 percent. This was 16.7 percent lower than M1, which had a lower SS:SH ratio of 1.5 and recorded a weight change of 1.2 percent, and 9.1 percent lower than M2, which had a moderate SS:SH ratio of 2.5 and recorded a weight change of 1.1 percent. The enhanced performance of M3 is attributed to the increased availability of silicate ions at higher SS:SH ratios, which promoted the formation of a dense and cohesive geopolymer gel, effectively reducing interconnected pores and minimizing sulphate ingress.

RCA mixes exhibited higher weight changes due to their porous structure and adhered mortar, which increase permeability and facilitate sulphate penetration. M7, which used 100 percent RCA and had an SS:SH ratio of 1.5, recorded the highest weight change of 1.8 percent. This value was 20 percent higher than M4, which used 50 percent RCA and recorded a weight change of 1.5 percent, and 50 percent higher than M1, which used 100 percent natural aggregates and recorded a weight change of 1.2 percent. The high weight change in M7 underscores the combined impact of RCA's porous nature and insufficient silicate ion availability at low SS:SH ratios, resulting in greater sulphate ion ingress and expansion.

However, the SS:SH ratio played a critical role in improving sulphate resistance in RCA mixes. For example, M9, which used 100 percent RCA and had an SS:SH ratio of 3.5, recorded a weight change of 1.4 percent. This represents a 22.2 percent reduction compared to M7, highlighting the effectiveness of a higher SS:SH ratio in densifying the geopolymer matrix and mitigating the adverse effects of RCA.

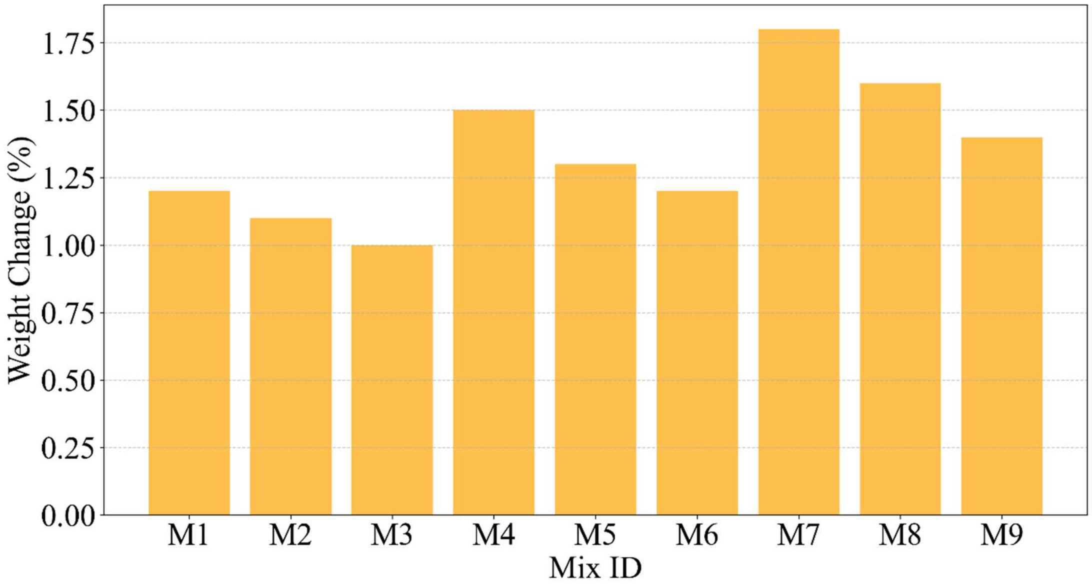

Figure 3 Weight change (%) of low molarity alkali activated concrete.

Residual Compressive Strength After Sulfate Attack

The residual compressive strength, expressed as the percentage of the original strength retained after sulphate exposure, provides further insights into the long-term durability of the mixes. Natural CA mixes retained a higher percentage of their original strength, showcasing their superior resistance to sulphate-induced deterioration. Among these, M3 retained 92 percent of its original strength, which was 4.5 percent higher than M1, which retained 88 percent, and 2.2 percent higher than M2, which retained 90 percent. The higher SS:SH ratio in M3 contributed to its superior performance by enhancing the density and cohesion of the geopolymer matrix, reducing sulphate ion penetration and minimizing microstructural damage.

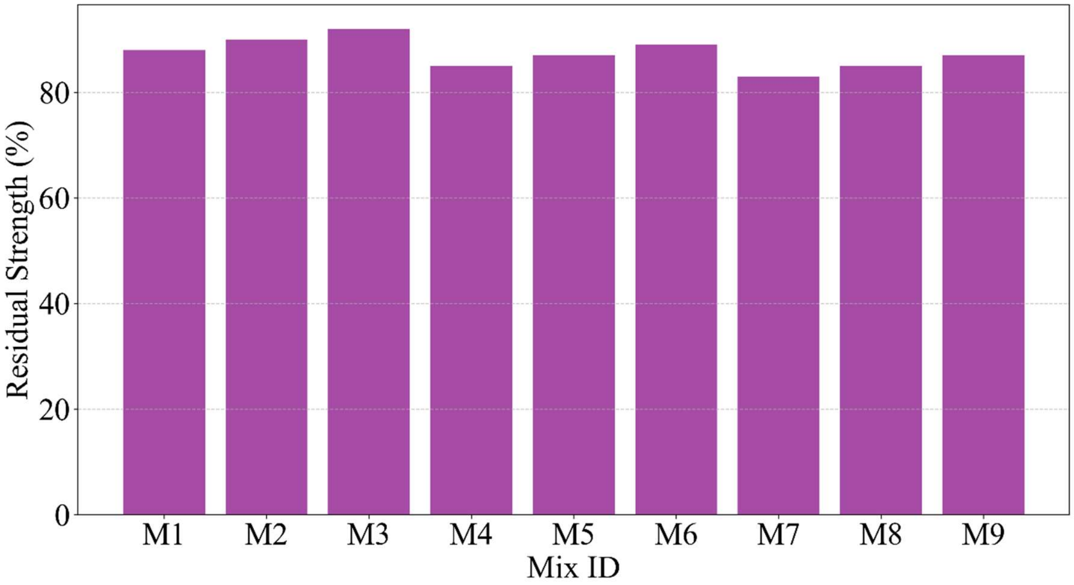

Figure 4 Residual strength (%) of low molarity alkali activated concrete.

RCA mixes retained lower percentages of their original strength due to their higher permeability and susceptibility to sulphate-induced deterioration. M7, which used 100 percent RCA and had a low SS:SH ratio of 1.5, retained only 83 percent of its original strength. This was 2.4 percent lower than M4, which used 50 percent RCA and retained 85 percent, and 5.7 percent lower than M1, which used 100 percent natural aggregates and retained 88 percent. The lower residual strength in M7 highlights the detrimental effects of RCA porous nature and the insufficient densification of the matrix at low SS:SH ratios, which allow sulphate ions to penetrate more easily, causing expansive reactions and reducing structural integrity.

Increasing the SS:SH ratio significantly improved the residual compressive strength of RCA mixes, demonstrating its critical role in enhancing durability. For instance, M9, which used 100 percent RCA and had an SS:SH ratio of 3.5 (Fig. 4), retained 87 percent of its original strength, representing a 4.8 percent improvement over M7. The higher SS:SH ratio contributed to better geopolymer gel formation, reducing the porosity and improving the bond between the recycled aggregates and the binder. This densification mitigated the adverse effects of sulphate attack, allowing the mix to maintain greater structural integrity.

Response surface methodology

The response surface analysis highlights the significant influence of the SS:SH ratio and RCA content on compressive strength (Fig. 5). Higher SS:SH ratios consistently improved strength across all RCA levels by enhancing geopolymerization and densifying the matrix. Natural aggregate mixes achieved the highest strength of 34 MPa at an SS:SH ratio of 3.5, while 100% RCA mixes exhibited the lowest strength (25.3 MPa), reflecting the weaker interfacial properties of RCA. However, increasing the SS:SH ratio mitigated RCA's impact, with 60% RCA mixes achieving 28 MPa at a 3.5 ratio. These findings demonstrate that optimizing the SS:SH ratio can effectively balance performance and sustainability, making alkali-activated concrete with RCA viable for structural applications.

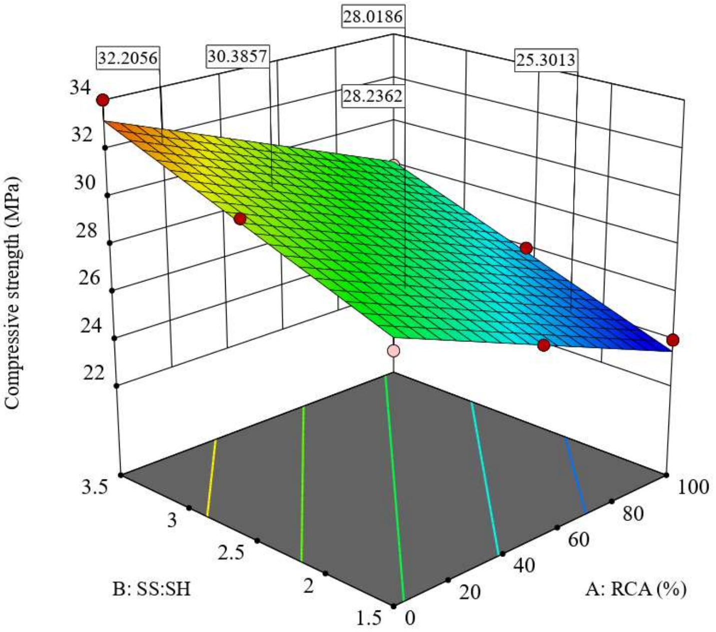

Figure 5 Compressive strength results of RSM.

Water absorption increased with higher RCA content due to the inherent porosity and weaker microstructure of recycled aggregates. At 100% RCA, the highest water absorption value of 3.08% was recorded (Fig. 6), reflecting the porous nature of the RCA and the adhered mortar. In contrast, natural aggregate mixes achieved the lowest water absorption of 2.0% at an SS:SH ratio of 3.5, demonstrating the enhanced matrix densification and reduced porosity. Increasing the SS:SH ratio effectively reduced water absorption across all RCA levels. For instance, at 60% RCA, water absorption decreased from 2.86% at a low SS:SH ratio of 1.5 to 2.50% at a ratio of 3.5, highlighting the role of silicate ions in filling voids and improving matrix compactness. These findings emphasize that optimizing the SS:SH ratio can mitigate the weaknesses of RCA and improve the durability of sustainable alkali-activated concrete.

Higher SS:SH ratios enhanced residual strength (Fig. 7), with natural aggregate mixes achieving the highest residual strength of 92% at an SS:SH ratio of 3.5. This indicates that a denser geopolymer matrix effectively mitigates sulphate attack by reducing sulphate ion penetration. RCA mixes exhibited lower residual strengths due to their higher porosity and weaker interfacial transition zones. At 100% RCA, the residual strength dropped to 83.7%, reflecting the susceptibility of RCA-based mixes to sulphate-induced deterioration. However, increasing the SS:SH ratio mitigated these effects. For instance, at 60% RCA, the residual strength improved from 86.6% at an SS:SH ratio of 1.5 to 90.1% at 3.5, highlighting the critical role of silicate ions in enhancing matrix densification and reducing chemical degradation.

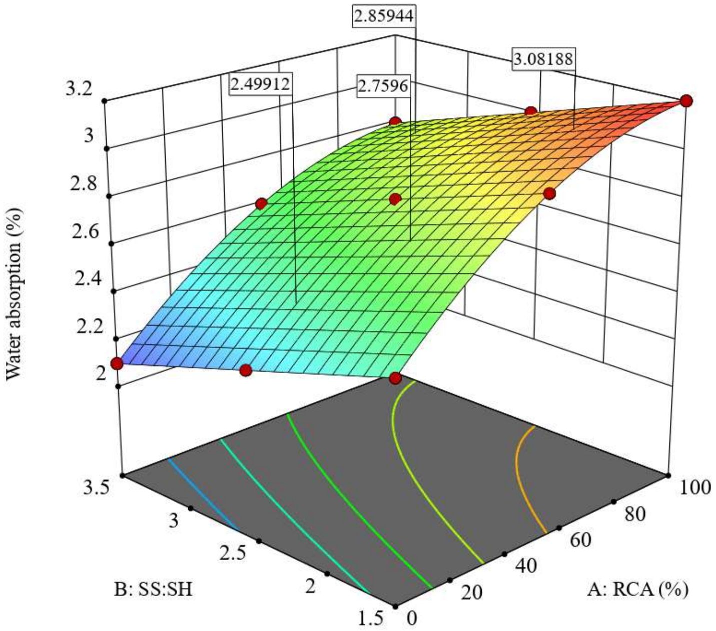

Figure 6 Water absorption results of RSM.

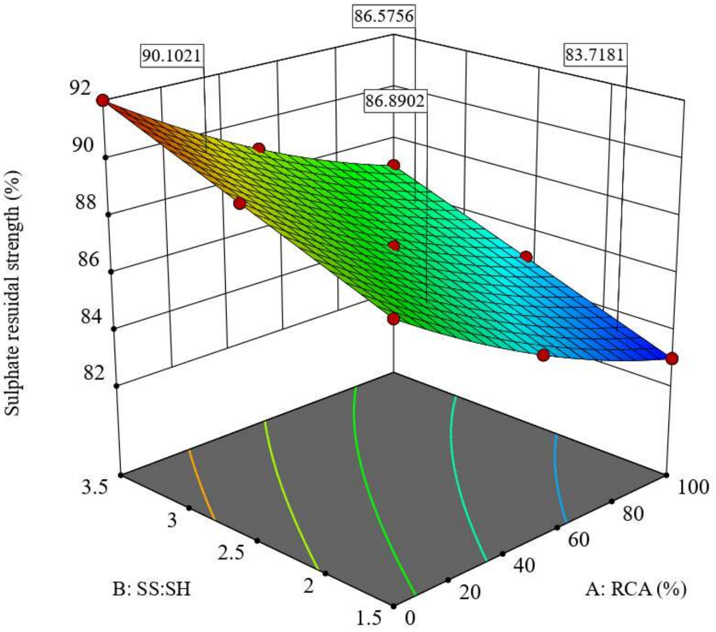

Figure 7 Sulphate residual strength results of RSM.

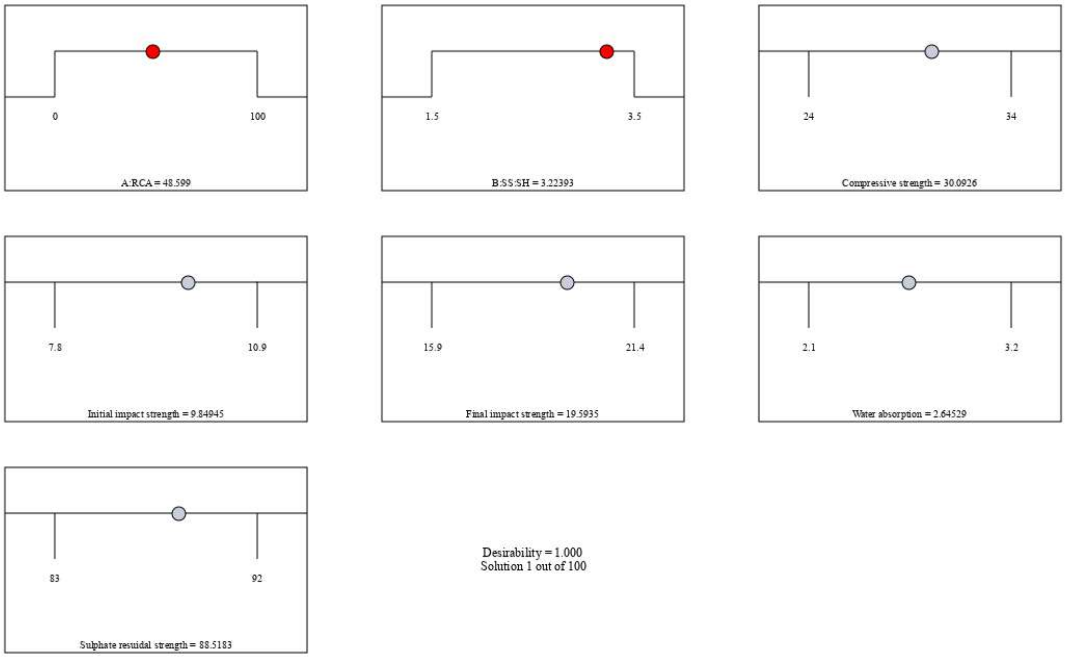

Figure 8 Ramp optimization results of RSM.

The optimization results (Fig. 8) from RSM identified an SS:SH ratio of 3.32 and an RCA content of 48.6% as the optimal mix, achieving a desirability of 1.0. This mix provided a compressive strength of 30.09 MPa, ensuring structural adequacy while balancing sustainability. The initial and final impact strengths of 9.85 kN-m and 19.59 kN-m, respectively, highlight the mix's ability to dissipate energy effectively under dynamic loads. Water absorption was maintained at 2.65%, demonstrating a dense and low-permeability matrix suitable for durability applications. Furthermore, the sulphate residual strength of 85.51% reflects the mix ability to resist chemical degradation, attributed to the enhanced matrix densification from the optimized SS:SH ratio. This combination mitigates the typical porosity and durability challenges associated with RCA, striking a balance between performance and environmental sustainability. The results emphasize the feasibility of integrating moderate RCA levels into high-performance alkali-activated systems for durable and eco-friendly construction.

Conclusions **and future directions**

This study explored the performance of alkali-activated concrete mixes with varying SS:SH ratios under low-molarity (2M) conditions, incorporating both CA and RCA. The results demonstrate the importance of the SS:SH ratio in enhancing the mechanical properties, durability, and overall performance of concrete mixes, particularly when addressing sustainability concerns using RCA.

- The SS:SH ratio emerged as a key factor influencing all major performance parameters. Higher ratios significantly improved the compressive strength, water absorption, and sulphate resistance of the mixes by enhancing the geopolymerization process. The increased availability of silicate ions facilitated the formation of a denser geopolymer matrix, reducing porosity, improving interfacial bonding, and mitigating the detrimental effects of both RCA and aggressive environments. This highlights the critical role of mix design optimization in achieving high performance with sustainable materials.
- Natural aggregate mixes consistently outperformed RCA-based mixes, reflecting the superior density, strength, and bond characteristics of natural aggregates. M3, with a high SS:SH ratio of 3.5, demonstrated exceptional results, achieving the best compressive strength, impact resistance, and durability across all metrics. Its performance underscores the potential of natural aggregate mixes for high-strength and durable structural applications.
- For RCA-based mixes, the SS:SH ratio was pivotal in narrowing the performance gap with natural aggregate mixes. Despite the inherent weaknesses of RCA, such as higher porosity and lower bonding strength, higher SS:SH ratios effectively compensated for these limitations by improving matrix densification and aggregate-binder interface bonding. M9, with 100 percent RCA and a high SS:SH ratio of 3.5, achieved a balanced performance in strength, durability, and impact resistance, making it a promising candidate for sustainable construction where recycled materials are prioritized.

- The use of low-molarity alkali-activated systems further highlights the environmental benefits of these mixes. The study demonstrates that even with a reduced alkalinity activator, satisfactory strength and durability can be achieved when the SS:SH ratio is optimized. This reduces both the environmental impact and safety concerns associated with high-molarity systems while maintaining functional performance.
- RSM optimization identified an SS:SH ratio of 3.32 and 48.6% RCA as the optimal mix, achieving a desirability of 1.0. This mix provided 30.09 MPa compressive strength, 2.65% water absorption, and 85.51% sulphate residual strength. These results demonstrate the feasibility of durable and sustainable RCA-based alkali-activated concrete.

Future research should focus on optimizing binder compositions by incorporating additional by-products such as silica fume or metakaolin to enhance geopolymerization. Advanced characterization techniques like SEM and XRD can provide insights into microstructural behaviour, while dynamic and long-term performance evaluations, including fatigue and chloride exposure tests, are essential for validating durability. Scaling these systems to full-scale structural applications and integrating hybrid aggregates can further balance sustainability and performance. Life-cycle assessments should quantify environmental benefits, and machine learning tools can optimize mix designs efficiently. Additionally, developing alternative low-molarity activators and exploring the integration of alkali-activated systems in smart city infrastructure will ensure their broader adoption in sustainable construction.

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