

Influence of Superabsorbent Polymer on Fresh and Hardened Properties of Rice Husk Ash-Blended Cement Concrete: A Review

^{1*}Oguntola I. O., ²Raheem A. A., ³Ikotun B. D. and ⁴Koku-Ojumu B. E.

^{1,4} Civil Engineering Department, Ladoke Akintola University of Technology, Ogbomoso, Nigeria.

² Department of Building, Ladoke Akintola University of Technology, Ogbomoso, Nigeria.

³ Department of Civil and Environmental Engineering and Building Science, University of South Africa.

* Corresponding Author E-mail: oguntolaisaiah@yahoo.com

Tel: 07032743530

Abstract

Rice husk ash (RHA), a silica-rich agricultural by-product with significant pozzolanic potential, has attracted increasing attention as a supplementary cementitious material for partial cement replacement in sustainable concrete production. Its incorporation can improve later-age strength, refine pore structure and reduce dependence on conventional cement. However, RHA often increases water demand, thereby reducing workability and delaying early-age strength development. Superabsorbent polymer (SAP), a hydrophilic material that absorbs and gradually releases water, offers a potential solution through internal curing. This review examines the influence of SAP on the fresh and hardened properties of RHA-blended cement concrete, with emphasis on workability, internal curing, mechanical performance, shrinkage behaviour, self-healing, microstructural development and durability-related properties. Evidence from the literature indicates that moderate SAP dosages may reduce workability by temporarily absorbing mixing water, while the subsequently released water sustains internal curing, enhances later-age strength development and reduces shrinkage-related cracking in RHA-blended concrete. Conversely, excessive SAP dosage may reduce workability and mechanical performance because of increased residual porosity. The review also highlights the importance of optimizing both RHA replacement level and SAP dosage to balance fresh and hardened properties. Overall, RHA-SAP blended cement concrete shows considerable potential as a sustainable, high-performance construction material. However, further studies are required on long-term durability, microstructural development and mixture optimization to support its wider application in structural concrete.

Keywords: Rice Husk Ash; Superabsorbent Polymer; Blended Cement Concrete; Fresh Properties; Hardened Properties

Introduction

The growing demand for sustainable and high-performance concrete has encouraged the use of supplementary cementitious materials and advanced admixtures in cement-based systems. Among these, rice husk ash (RHA) offers environmental and pozzolanic benefits, while superabsorbent polymer (SAP) provides internal-curing potential through controlled water absorption and release. This section introduces the generation and processing of RHA, its application in cementitious composites, the role of SAP in concrete, and the rationale for reviewing their combined use.

Agricultural Residues and Rice Husk Generation

Agricultural production generates large quantities of crop residues that are often underutilized or disposed of through open burning and landfilling. When appropriately processed, residues such as rice husk, sugarcane bagasse, palm-oil residues, wheat straw, millet husk, wood waste and corn cob can yield ashes with silica- and alumina-bearing phases that are suitable for use as supplementary cementitious materials (SCMs). Their utilization in cementitious composites can simultaneously reduce waste-disposal burdens and lower the demand for Portland cement (Raheem and Ikotun, 2020; Biswas *et al.*, 2026). Among these residues, rice husk is particularly important because of its abundance and naturally high silica content.

Rice husk is the tough protective outer covering removed from paddy rice during milling and typically represents about one-fifth of the mass of paddy grain. This distinction is important because estimates of husk generation should be related to paddy-rice production rather than directly to milled-rice output. Rice-producing regions therefore generate large quantities of rice husk annually, creating both a disposal challenge and a potentially valuable raw material stream. As illustrated in Fig. 1, the recovered husk can be converted into rice husk ash (RHA) through controlled calcination, commonly within a temperature range of about 500-700 °C. This process removes most of the organic fraction while preserving a high proportion of reactive silica, producing a lightweight, porous and silica-rich ash that can be utilized as a supplementary cementitious material in concrete production (Barbhuiya *et al.*, 2025; Jing *et al.*, 2025; Biswas *et al.*, 2026).

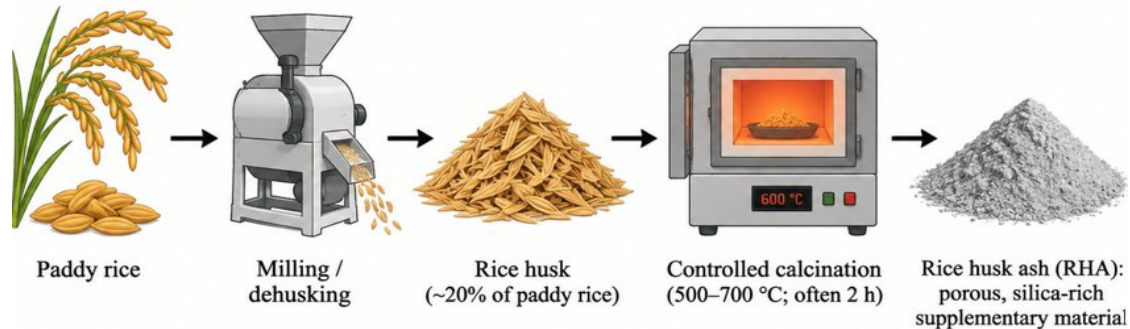


Figure 1: Rice husk generation and controlled processing route to rice husk ash

Production and Characteristics of Rice Husk Ash

The performance of RHA in cement-based materials is governed largely by the way the husk is burned and the resulting ash is cooled and ground. Recent reviews indicate that controlled combustion in the approximate range of 500-700 °C favours the retention of amorphous silica, while several production studies adopt a burning duration of about 2 h. Temperatures substantially above this range can promote crystallization of silica, whereas inadequate temperature or insufficient burning time may leave excessive unburnt carbon. Grinding subsequently increases fineness and reactive surface area, although excessive fineness can also increase water demand (Jing *et al.*, 2025).

Properly processed RHA is generally porous, irregular in morphology and rich in silica, with its chemical composition, loss on ignition, particle size and specific surface area strongly influencing pozzolanic reactivity. Reactive silica consumes calcium hydroxide released during cement hydration and contributes to the formation of additional calcium-silicate-hydrate (C-S-H), thereby refining the pore structure and supporting later-age strength and durability. Recent syntheses also show that the quality of agro-waste ashes varies with feedstock source and processing conditions, reinforcing the need for controlled production and characterization before use in concrete (Barbhuiya *et al.*, 2025; Biswas *et al.*, 2026).

Application of RHA in Cement-Based Composites

RHA has been incorporated into a wide range of cement-based materials, including mortar, conventional concrete, self-compacting concrete, high-performance and ultra-high-performance concrete, recycled-aggregate concrete, and ternary or quaternary blended-binder systems. Recent reviews indicate that replacement levels in the broad range of about 10-20% are frequently associated with favourable performance, although the optimum content is highly dependent on ash quality, fineness, water-to-binder ratio, curing regime and the presence of other mineral or chemical admixtures (Barbhuiya *et al.*, 2025; Jing *et al.*, 2025).

Despite its sustainability and later-age performance benefits, RHA commonly increases water demand because of its porous structure and high surface area. As the RHA fraction increases, fresh concrete may therefore exhibit lower slump and greater viscosity unless the mixture is appropriately adjusted. The same

high reactivity that benefits later-age properties can also be accompanied by slower early strength development when clinker is substantially displaced. These characteristics make moisture management and mixture proportioning central to the successful use of RHA-containing concrete.

Superabsorbent Polymers in Cementitious Materials

Superabsorbent polymers are cross-linked hydrophilic polymer networks that can absorb and retain substantial amounts of water. Sodium-polyacrylate-based materials are commonly investigated for cementitious applications, and their absorption capacity depends on polymer chemistry, cross-link density, particle size and the ionic composition of the surrounding pore solution. As shown in Fig. 2, dry SAP absorbs some mixing water in the fresh state, reducing the free water available for particle lubrication and potentially decreasing workability. As hydration progresses and the internal relative humidity decreases, the absorbed water is gradually released into the surrounding cementitious matrix, providing internal curing water that sustains hydration and limits self-desiccation (Mechtcherine *et al.*, 2018; Mechtcherine *et al.*, 2021; Schröfl *et al.*, 2022).

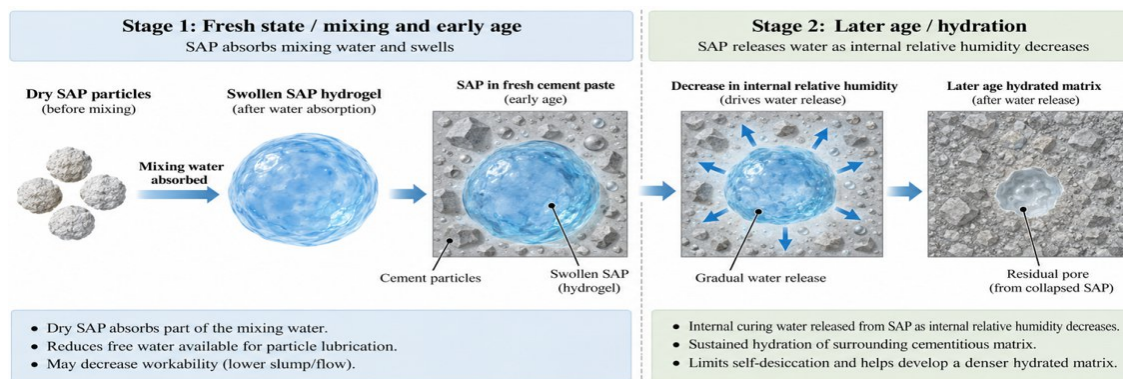


Figure 2: Water absorption and release mechanism of SAP in cementitious systems

This water-storage mechanism has made SAP useful for internal curing, autogenous-shrinkage mitigation and self-healing applications. Nevertheless, its benefits are dosage dependent. Excessive SAP contents can cause pronounced fresh-state workability loss and leave residual macropores after desorption, thereby offsetting hydration benefits and reducing mechanical performance. Consequently, SAP dosage and any additional curing water must be considered together during mixture design (De Meyst *et al.*, 2019; Zhou *et al.*, 2024).

Rationale and Scope of the Review

The combined use of RHA and SAP is not entirely new. For example, Nduka *et al.* (2022) investigated high-performance concrete containing RHA and internally cured with SAP and reported beneficial later-age mechanical and microstructural responses at appropriate RHA contents. However, direct RHA-SAP studies remain limited relative to the much larger bodies of literature on RHA and SAP separately, and reported outcomes vary with material properties, dosage, water compensation and curing conditions. Accordingly, this review critically examines the influence of SAP on the fresh and hardened properties of RHA-blended cement concrete. Emphasis is placed on workability, internal curing, hydration and mechanical performance, shrinkage behaviour, self-healing, microstructural development and durability. The review also evaluates the mechanisms through which RHA and SAP interact and identifies research needs that must be resolved before wider structural application.

Review Methodology

This review adopted a structured literature-based approach to identify, evaluate and synthesize relevant studies on rice husk ash (RHA), superabsorbent polymer (SAP) and their combined application in cementitious materials. The methodology was designed to ensure that the reviewed literature was relevant to the study objectives and provided sufficient coverage of the fresh, hardened, durability and microstructural properties of RHA-SAP blended cement concrete.

Search strategy

Relevant literature was identified through Google Scholar, ScienceDirect, SpringerLink, Scopus and Web of Science. Search terms included combinations of rice husk ash concrete, superabsorbent polymer, RHA-SAP concrete, internal curing, workability, fresh properties, hardened properties, shrinkage, self-healing, microstructure and durability. Primary emphasis was placed on peer-reviewed studies published from 2018 to 2026 so that the synthesis reflected current knowledge and recent developments.

Eligibility and thematic classification

Peer-reviewed journal articles and relevant conference papers were considered where they examined RHA, SAP or their combined application in cementitious materials and reported information on fresh, mechanical, durability or microstructural behaviour. Studies were screened for direct relevance to the review objectives, and the selected evidence was grouped into thematic areas covering material characteristics, workability and rheology, internal curing and shrinkage, mechanical performance, self-healing, microstructure and field-scale application.

Comparative synthesis

The selected studies were comparatively analyzed to identify consistent trends, contradictory findings and variables responsible for differences in reported performance. Attention was given to RHA processing and replacement level, SAP particle characteristics and dosage, water compensation and curing conditions. The synthesis was then used to clarify the individual and combined mechanisms of RHA and SAP and to identify research gaps requiring further investigation.

Literature Synthesis and Discussion

Literature synthesis examines the major themes emerging from previous studies on RHA and SAP, with emphasis on their material characteristics, interaction mechanisms and influence on concrete performance. The discussion is organized to compare reported findings, identify areas of agreement and variation, and relate these observations to the behaviour of RHA-SAP blended cement concrete.

Physio-chemical properties of RHA and SAP

Recent literature consistently describes RHA as a lightweight, irregular and highly porous ash whose effectiveness as an SCM depends on controlled combustion and adequate grinding. High-quality RHA is dominated by amorphous silica, while fineness and specific surface area influence both its filler effect and pozzolanic reactivity. The same porous morphology that promotes reactivity also increases water demand and can reduce fresh-state workability. When the combined SiO_2 , Al_2O_3 and Fe_2O_3 content satisfies the $\geq 70\%$ chemical criterion commonly used in assessing pozzolanic materials under ASTM C618, RHA demonstrates chemical characteristics consistent with a highly siliceous pozzolan. (ASTM International, 2019; Barbhuiya *et al.*, 2025; Biswas *et al.*, 2026). SAP differs fundamentally from RHA because it is not a pozzolan but a moisture-regulating polymer. Its cross-linked hydrophilic network swells by absorbing water and later releases part of that water when the internal relative humidity of the cementitious matrix decreases. Absorption in cement pore solution is typically lower than in deionized water because dissolved ions affect polymer swelling; therefore, SAP performance should be characterized under representative cementitious conditions. Particle size, cross-link density, dosage and water compensation all influence the balance between internal-curing benefit, workability loss and residual pore formation (Mechtcherine *et al.*, 2018; Mechtcherine *et al.*, 2021; Schröfl *et al.*, 2022; Zhou *et al.*, 2024).

When used together, RHA and SAP provide complementary but potentially competing effects. RHA contributes reactive silica that consumes $\text{Ca}(\text{OH})_2$ and generates secondary C-S-H, while SAP can maintain internal moisture for continued cement hydration and the pozzolanic reaction. At the fresh stage, however, both materials can increase the demand for available mixing water. Direct RHA-SAP evidence therefore supports a mixture-design approach that balances RHA reactivity with SAP-mediated moisture regulation rather than maximizing either component independently (Nduka *et al.*, 2022). The principal characteristics of RHA that influence its behaviour in blended cement concrete, including its physical, chemical, fresh and mechanical effects, are summarized in Table 1.

Table 1: Summary of Key Properties and Effects of Rice Husk Ash (RHA) in Blended Cement Concrete

Category	Key property	Effect on blended cement concrete	References
General	SCM incorporation	Properly processed RHA can partially replace Portland cement, thereby reducing cement demand and supporting lower-carbon concrete production.	Biswas <i>et al.</i> (2026); Barbhuiya <i>et al.</i> (2025)
Physical	Fineness	Increased fineness enhances surface area and pozzolanic reactivity, although excessive fineness may increase water demand.	Jing <i>et al.</i> (2025); Barbhuiya <i>et al.</i> (2025)
Physical	Density and porosity	RHA is relatively lightweight and porous, characteristics that influence particle packing, water absorption and fresh-state water demand.	Biswas <i>et al.</i> (2026); Barbhuiya <i>et al.</i> (2025)
Fresh	Workability	Increasing RHA content generally reduces workability because of its high surface area and porous particle morphology.	Raheem and Anifowose (2023); Jing <i>et al.</i> (2025)
Fresh	Setting behavior	RHA content and fineness can influence consistency and setting behaviour through dilution, water absorption and pozzolanic effects.	Raheem and Anifowose (2023)
Chemical	Silica content	Properly processed RHA is rich in reactive amorphous silica, which largely governs its pozzolanic activity.	Barbhuiya <i>et al.</i> (2025); Jing <i>et al.</i> (2025)
Chemical	Oxide composition	The combined $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content may satisfy the $\geq 70\%$ chemical criterion commonly used in assessing pozzolanic materials under ASTM C618.	ASTM International (2019); Biswas <i>et al.</i> (2026)
Chemical reaction	Pozzolanic activity	Reactive silica consumes $\text{Ca}(\text{OH})_2$ and contributes to the formation of additional C-S-H, thereby refining the cementitious matrix.	Barbhuiya <i>et al.</i> (2025); Jing <i>et al.</i> (2025)
Mechanical	Compressive strength	Favourable later-age strength is commonly reported at moderate RHA replacement levels, often around 10–20%, depending on ash quality and mixture design.	Barbhuiya <i>et al.</i> (2025); Jing <i>et al.</i> (2025)

Application of SAP in Concrete

SAP is used in cementitious materials primarily as an internal-curing agent, but its effects extend to fresh-state rheology, shrinkage control, self-healing, microstructure and durability. The magnitude and direction of these effects depend on whether the polymer is dry or pre-saturated, its absorption capacity in pore solution, particle size, dosage and the amount of additional water supplied. The following subsections discuss the major applications.

Internal curing and shrinkage mitigation

Internal curing is the most established application of SAP in concrete. As hydration consumes capillary water and internal relative humidity falls, swollen SAP particles release stored water and reduce self-desiccation. Recent reviews and experimental studies show that appropriately dosed SAP can substantially reduce autogenous shrinkage and early-age cracking in low-water-to-binder and high-performance mixtures while sustaining hydration (Mechtcherine *et al.*, 2021; Schröfl *et al.*, 2022; Zhou *et al.*, 2024). Tenório

Filho *et al.* (2024) further demonstrated in reinforced-concrete wall trials that SAP-assisted internal curing can reduce shrinkage-cracking susceptibility and associated reinforcement-corrosion risk. These benefits are especially relevant to RHA-containing systems because continued moisture availability can also support the slower pozzolanic reaction of RHA.

Workability and rheology

The influence of SAP on workability is strongly governed by its condition at mixing. Dry SAP rapidly absorbs part of the mixing water and can reduce slump or flow, whereas pre-saturated SAP introduces stored water and may produce a smaller workability loss or, in some systems, a temporary increase in flow. Finer particles generally hydrate more rapidly than coarse particles and can therefore exert a stronger immediate effect on the rheology of the fresh mixture. Recent syntheses emphasize that workability cannot be interpreted from SAP dosage alone; polymer absorption in cement pore solution and the amount of compensating water must also be considered (Zhou *et al.*, 2024; Lyu *et al.*, 2025). In RHA-SAP concrete, this issue is amplified because RHA itself has a high-water demand.

Mechanical strength and hydration dynamics

SAP produces competing effects on mechanical performance. Internal curing can improve the degree of hydration and reduce damage from early self-desiccation, but voids remaining after water release act as macropores that may reduce strength. De Meyst *et al.* (2019) demonstrated that increasing SAP content can lower compressive strength when pore formation outweighs the internal-curing benefit. Conversely, properly balanced SAP-water systems can preserve or improve later-age performance by sustaining hydration (Mechtcherine *et al.*, 2021; Zhou *et al.*, 2024). In RHA-containing high-performance concrete, Nduka *et al.* (2022) reported denser later-age microstructures and improved mechanical performance at suitable RHA levels under SAP-assisted internal curing, showing that the two materials can be compatible when proportioned appropriately.

Self-healing concrete and crack autonomy

SAP can also support autonomous crack sealing. When water enters a crack, exposed SAP swells and physically restrict water flow; subsequent water release can promote continued hydration and precipitation of crack-filling products. Hong *et al.* (2020) reported substantial recovery of watertightness in SAP-modified cracked cementitious materials, while Suleiman *et al.* (2021) showed that the degree of autogenous healing is strongly affected by temperature and relative humidity. More recent work in alkali-activated systems and SAP-modified mortars confirms that polymer swelling, moisture storage and precipitation mechanisms can contribute to crack closure and reduced transport through healed cracks (Yang *et al.*, 2023; Lyu *et al.*, 2025).

Microstructure refinement and transport properties

Microstructural development in SAP-modified materials reflects a balance between enhanced hydration around the internal reservoirs and the macropores left after desorption. Imaging studies show that the additional curing water can support a more continuous hydration-product network in the surrounding paste, while the size and distribution of SAP-generated voids determine whether the net effect is beneficial or detrimental. Lefever *et al.* (2020) and Mechtcherine *et al.* (2021) reported that suitable SAP systems can improve hydration continuity and influence pore connectivity. In RHA-SAP systems, the secondary C-S-H formed through the pozzolanic reaction may further refine the surrounding matrix, as observed in direct RHA-SAP high-performance concrete studies (Nduka *et al.*, 2022).

Field applications and case studies

Evidence from structural-scale and field-oriented studies indicates that SAP technology can move beyond laboratory specimens. The RILEM state-of-the-art update documents applications and demonstration projects in which SAP was used to control shrinkage and support internal curing in large concrete elements

(Mechtcherine *et al.*, 2021). Tenório Filho *et al.* (2024) provided further field-relevant evidence from reinforced-concrete wall elements, where crack mitigation was associated with improved corrosion performance. Zhou *et al.* (2024) similarly concluded that SAP has practical potential for pavement and structural applications, although field performance remains sensitive to polymer properties, dosage, water compensation and the host concrete mixture.

Evidence from Nigerian Studies on RHA and SAP-Modified Cementitious Materials

Nigerian researchers have contributed significantly to the understanding and application of rice husk ash (RHA) and superabsorbent polymer (SAP) in cementitious materials. Earlier studies focused mainly on establishing the suitability of locally produced RHA as a supplementary cementitious material, whereas more recent investigations have extended this research to internal curing using SAP and the combined behaviour of RHA-SAP systems. These studies are particularly important because the properties and performance of RHA depend strongly on the source of the rice husk, combustion conditions, particle fineness and subsequent processing. Consequently, investigations involving locally sourced materials provide useful information for developing sustainable cementitious materials that are suitable for Nigerian construction conditions.

Raheem and Kareem (2017) investigated the chemical composition and physical characteristics of RHA-blended cement containing different RHA replacement levels. Their findings confirmed the pozzolanic potential of the ash, with the combined SiO_2 , Al_2O_3 and Fe_2O_3 content exceeding 70%. The study also considered fineness, soundness, consistency, initial and final setting times, and compressive strength at different curing ages. Although increasing RHA content was associated with lower early-age strength, the contribution of the pozzolanic reaction became more evident at later ages. The authors reported that RHA replacement of up to approximately 15% satisfied the strength activity requirements considered in the study, indicating its potential for use in structural cementitious applications. These findings emphasize the importance of both the chemical composition and physical characteristics of RHA in determining its performance as a supplementary cementitious material.

The influence of RHA on the fresh properties of concrete has also received considerable attention in Nigeria. Adenuga *et al.* (2010) examined the use of RHA as a partial replacement for cement and reported noticeable changes in concrete workability. The reduction in workability was associated with the water-absorbing characteristics of RHA, although suitably proportioned mixtures were still capable of developing adequate compressive strength. Similarly, Adina *et al.* (2019) evaluated the strength and workability of concrete containing 2-12% RHA. Their results showed that workability progressively decreased as RHA content increased. A 7% RHA addition produced favourable strength without a substantial loss in initial workability, whereas higher RHA contents resulted in increasingly dry mixtures. These observations demonstrate the importance of considering the additional water demand associated with RHA when proportioning fresh concrete mixtures.

The effect of RHA on water requirement and setting behaviour was examined more specifically by Raheem and Anifowose (2023). They investigated RHA at different levels of fineness and replacement contents ranging from 10 to 50%, with particular attention to consistency and initial and final setting times. Their findings showed that the behaviour of RHA-blended cement cannot be explained solely by the percentage of cement replacement because ash fineness also influences water demand and setting characteristics. This observation is particularly relevant to RHA-SAP systems because SAP also interacts strongly with the mixing water. In such systems, water is required both for wetting the porous RHA particles and for absorption by SAP during the fresh stage. Consequently, RHA fineness, SAP dosage and the amount of available or compensating water may collectively influence workability and setting behaviour.

More recent Nigerian evidence further shows that the setting response of RHA-containing cementitious materials can vary with material characteristics and mixture proportions. Ambrose *et al.* (2026) investigated concrete containing RHA at replacement levels ranging from 0 to 25%. Their results indicated that initial setting time increased with RHA incorporation, which was associated with the reduction in the cement fraction responsible for early hydration and the comparatively slower reaction of the pozzolanic material. The reported behaviour of final setting time did not follow the same trend as the initial setting response. This variation demonstrates that the effect of RHA on setting should not be generalized without considering factors such as ash characteristics, replacement level, mixture composition and testing conditions. Such differences also reinforce the need to investigate the influence of SAP, since its water-absorption and release characteristics can further modify the hydration environment and setting behaviour of RHA-containing systems.

Nigerian researchers have also contributed directly to the study of SAP as an internal-curing material. Olawuyi *et al.* (2020) compared SAP and pre-soaked pumice as internal-curing agents in RHA-based high-performance concrete. SAP was incorporated at 0.3% by weight of binder, and the study demonstrated the feasibility of using SAP for internal curing in concrete containing RHA. The significance of this investigation lies in the interaction between the two materials. RHA provides reactive silica that participates in pozzolanic reactions, while SAP serves as an internal water reservoir capable of releasing stored moisture as hydration progresses. This interaction is particularly important in high-performance concrete with a low water-to-binder ratio, where self-desiccation may restrict continued hydration if sufficient internal moisture is not available.

Nduka *et al.* (2020) further examined the influence of SAP on high-performance concrete incorporating active supplementary cementitious materials available in Nigeria. Their work was partly directed towards the use of locally available materials as alternatives to conventional supplementary materials that may be relatively expensive or less readily available. This approach highlights the sustainability advantage of combining locally sourced agricultural pozzolans with SAP. In this context, SAP functions not merely as a conventional admixture but as an internal-curing material that can help address moisture-related limitations in concrete containing highly absorptive supplementary cementitious materials.

A subsequent study by Nduka *et al.* (2022) provided more detailed evidence on high-performance concrete containing RHA and internally cured with SAP. RHA replacement levels from 0 to 30% were investigated at a constant water-to-binder ratio of 0.30, and the fresh, mechanical and microstructural properties of the mixtures were evaluated. The study reported that the mixture containing 10% RHA achieved the highest compressive strength among the investigated RHA mixtures across the curing ages considered. Microstructural investigations using XRD and SEM/EDX also indicated continued development of the cementitious matrix, including a reduction in calcium hydroxide associated with pozzolanic reaction and the formation of additional calcium-silicate-hydrate (C-S-H). The study further reported that mixtures containing approximately 5-20% RHA satisfied the specified slump-flow requirement, whereas maintaining workability became more challenging at higher RHA replacement levels. These findings provide important Nigerian evidence linking fresh behaviour, mechanical performance and microstructural development in SAP-internally cured RHA concrete.

Other Nigerian investigations have similarly demonstrated the sensitivity of RHA concrete to mixture proportioning. Studies involving RHA in combination with alternative aggregates have generally reported reductions in workability relative to corresponding control mixtures, while later-age strength may benefit from continued pozzolanic activity. Such findings agree with the broader understanding that the sustainability and pozzolanic benefits of RHA do not necessarily result in improved fresh properties. Instead, its porous structure, high specific surface area and associated water demand must be considered during mixture design. This requirement becomes even more important when dry SAP is incorporated because the polymer can temporarily absorb and retain part of the mixing water during the fresh stage.

Taken together, Nigerian studies demonstrate that RHA has considerable potential as a locally available supplementary cementitious material, but its performance is strongly influenced by processing conditions, fineness, replacement level, water demand and curing conditions. Emerging Nigerian research on SAP further indicates that internal curing can complement RHA-containing cementitious systems by maintaining moisture availability as hydration progresses. Nevertheless, direct studies examining the combined use of RHA and SAP remain relatively limited when compared with the larger body of research investigating either material independently. In addition, differences in RHA characteristics, SAP type and dosage, water-to-binder ratio, water compensation and curing conditions make direct comparison among existing studies difficult.

Further research is therefore required to establish how SAP chemistry, particle size, absorption capacity and dosage interact with locally produced RHA having different fineness and replacement levels. Attention should be given to fresh-state water availability, workability, setting behaviour, strength development, SAP-induced residual pores and long-term durability. Future investigations should also consider standardized approaches to water compensation and SAP characterization so that results from different studies can be compared more reliably. Such research would assist in establishing practical mixture-design guidance that balances the pozzolanic benefits of RHA with the internal-curing function of SAP while avoiding excessive reductions in workability or mechanical performance. Nigerian research therefore provides an important foundation for developing RHA-SAP blended cement concrete while also revealing the need for more systematic investigations that simultaneously address fresh, hardened, durability and microstructural performance.

Conclusion

The reviewed studies collectively demonstrate that the performance of RHA-SAP blended cement concrete is governed by the interaction between the pozzolanic contribution of RHA and the internal-curing function of SAP. Based on the evidence synthesized in this review, the following conclusions are drawn:

- i. The reviewed literature shows that RHA and SAP act through complementary mechanisms, with RHA contributing pozzolanic C-S-H formation and SAP providing internal curing water to sustain hydration.
- ii. Moderate SAP dosages can improve shrinkage control and later-age performance, while excessive SAP may reduce workability and create residual pores that adversely affect strength.
- iii. The performance of RHA-SAP concrete depends on RHA processing and replacement level, SAP characteristics and dosage, and water compensation; therefore, no single optimum combination can be applied universally.

Recommendations

Based on the findings and research gaps identified from the reviewed literature, the following recommendations are proposed to guide future studies and support the effective application of RHA-SAP blended cement concrete:

- i. Future studies should jointly optimize RHA replacement, SAP dosage and water compensation to achieve a suitable balance between workability, strength and durability.
- ii. Long-term studies should evaluate chloride ingress, carbonation, sulfate resistance, elevated-temperature behaviour and reinforcement corrosion in RHA-SAP concrete.
- iii. Further microstructural investigations should be conducted to clarify the relationship among SAP water release, RHA pozzolanic reaction and residual pore formation.

- iv. Field-scale studies are recommended to support wider structural application and the development of practical design guidelines.

Contributions to knowledge

This review contributes to existing knowledge by bringing together and critically synthesizing current findings on the combined use of RHA and SAP in cementitious systems. The key contributions of the review are summarized as follows:

- i. The review integrates available evidence on the combined use of RHA and SAP with the broader literature on both materials.
- ii. It clarifies the interaction between RHA-induced water demand and pozzolanic activity and SAP-induced internal curing and pore development.
- iii. It identifies the major variables controlling RHA-SAP concrete performance, including RHA processing, replacement level, SAP characteristics, dosage and water compensation.
- iv. It highlights key research gaps in durability, microstructural development, elevated-temperature behaviour, field validation and mixture optimization.

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