RESEARCH PAPER

Characteristics and Analysis of Self-Compacting Concrete Using Rice Husk Ash and Fly Ash with Artificial Neural Network

[1]Vishvanath Nandkumar Kanthe, [2]Sachin Sopan Patil and [3]Vrinda Santosh Bhalerao

[1]PhD, Associate Professor, Department of Civil Engineering, Guru Gobind Singh College of Engineering and Research Center Nashik
[2]PhD, Assistant Professor, Department of Civil Engineering, MET's Institute of Engineering, Bhujabal knowledge city Nashik.
[3]PhD, Assistant Professor, Department of Civil Engineering, Guru Gobind Singh College of Engineering and Research Center Nashik
[1]kanthetech@gmail.com, [2]sachinpatil180784@gmail.com and [3]Vrinda.bhalerao86@gmail.com

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ABSTRACT

Self-compacting concrete (SCC) is designed to flow, fill, and compact under its own weight, pass through heavily reinforced areas, and remain stable without segregation. Incorporating supplementary cementitious materials such as fly ash (FA) and rice husk ash (RHA) offers a practical route to improve sustainability while influencing both fresh and hardened concrete properties. This paper develops a 12-page review-oriented manuscript on the behavior and analytical assessment of SCC containing FA and RHA. The discussion is organized into three major parts: (i) a synthesis of existing literature on workability, strength, and durability; (ii) a proposed methodological framework covering material characterization, mix design, fresh-state testing, hardened-state evaluation, and durability assessment; and (iii) an analytical framework based on response surface methodology (RSM), artificial neural networks (ANN), and adaptive neuro-fuzzy inference systems (ANFIS).The literature reviewed reveals a fairly consistent trend. Fly ash generally improves flowability and contributes to strength gain at later ages, whereas rice husk ash often reduces fresh workability because of its high fineness and porous texture, although it can enhance later-age strength and durability when used at appropriate levels. A recurring observation across representative studies is that RHA is usually most beneficial at moderate replacement levels, commonly around 15–20% in SCC, while FA often performs well in the range of 20–30%, particularly when supported by suitable superplasticizer dosage and a controlled water-to-binder ratio. In combined systems, FA and RHA may act in a complementary manner: FA tends to improve particle packing and rheological behavior, while RHA provides reactive amorphous silica that helps densify the cement matrix. In summary, the paper finds that SCC containing both FA and RHA is technically feasible and environmentally advantageous, but its effective use depends on proper mix proportioning, compliance with EFNARC fresh-property requirements, and data-driven optimization through RSM, ANN, or ANFIS to achieve an appropriate balance among filling ability, viscosity, strength, and durability.

Keywords: *self-compacting concrete; rice husk ash; fly ash; supplementary cementitious materials; workability; durability; ANFIS; ANN; RSM; sustainable concrete.*

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1. INTRODUCTION

Concrete plays a vital role in modern infrastructure, yet the manufacture of cement places considerable pressure on the environment. A common and effective engineering solution is to replace a portion of ordinary Portland cement (OPC) with supplementary cementitious materials (SCMs), particularly those derived from industrial and agricultural waste that might otherwise pose disposal challenges.

Self-compacting concrete has become highly significant in the transition toward sustainable construction practices. It is able to flow into formwork under its own weight, move through congested reinforcement without blockage, and remain uniform without the use of external vibration . Because of these properties, it is well suited to heavily reinforced structural members, precast elements, architectural applications, repair works, and construction settings where vibration is either difficult or undesirable. At the same time, SCC is highly responsive to factors such as powder content, particle-size distribution, paste volume,

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**Author for Correspondence: Vishvanath Nandkumar Kanthe* aggregate grading, and admixture dosage. Therefore, the introduction of alternative powder materials can have a much stronger effect on both fresh-state and hardened performance than in conventional vibrated concrete.

Fly ash is widely recognized as one of the most frequently used supplementary cementitious materials in self-compacting concrete. It is often credited with improving workability because of its near-spherical particle form, while its pozzolanic behavior also supports strength development at later ages. Recent research on SCC suggests that, with proper control of replacement dosage, fly ash mixtures can provide a well-balanced combination of slump flow, viscosity, passing ability, compressive strength, and resistance to chloride ingress.Rice husk ash is a by-product of the controlled combustion of rice husk.

When processed under suitable conditions, it contains a high percentage of amorphous silica and acts as a highly reactive pozzolanic material. In self-compacting concrete, however, its use can also introduce practical limitations, as its very fine and porous particles raise water demand and often decrease slump flow and L-box values unless proper modifications are made to the superplasticizer dosage and water-to-binder ratio.The engineering basis for combining fly ash and rice husk ash lies in the way their effects complement one another. Fly ash tends to promote better particle packing and smoother flow, whereas rice husk ash helps improve binder densification and pore refinement. When these two materials are used in suitable proportions, they can reduce clinker usage, retain the fresh-state performance expected of SCC, and improve later-age strength as well as durability. With this background, the paper explores the following question: how can the performance of self-compacting concrete containing fly ash and rice husk ash be interpreted and optimized through the combined use of materials engineering principles and predictive analytical tools.

2. LITERATURE REVIEW

Studies examining SCC with treated RHA under different curing temperatures add further depth to this understanding. Open-access evidence published in 2024 suggests that RHA-based SCC is strongly influenced by curing conditions: higher temperatures tend to speed up early hydration and strength gain, while lower temperatures slow initial development but may still lead to considerable later-age strength as supplementary cementitious reactions continue over time . This observation is important because, in practical construction, SCC is often exposed to non-isothermal curing environments, so optimum binder design must be considered together with thermal history rather than in isolation.For fly ash, the literature generally indicates enhanced flowability together with solid strength development at later ages. A recent *Scientific Reports* investigation on fly ash–based SCC reported an optimum replacement level of nearly 30% in the system studied; beyond this threshold, reductions in early-age strength became more evident because the dilution effect started to outweigh the rheological and pozzolanic benefits . The same study also showed that fresh-property measurements satisfied EFNARC requirements, while the most favorable ternary mixes achieved clear durability improvements, including lower sorptivity and reduced chloride permeability.

Experimental investigations on self-compacting concrete containing treated rice husk ash under different curing temperatures offer additional understanding of this behavior. Open-access evidence published in 2024 suggests that SCC mixtures with RHA are strongly affected by curing conditions: elevated temperatures encourage faster early hydration and quicker strength gain, whereas lower temperatures slow early-age development but can still result in substantial later-age strength as supplementary cementitious reactions continue over time . This has practical significance because many SCC systems in real construction are subjected to non-isothermal curing, so optimum binder design needs to be evaluated in conjunction with the material's thermal history.

Recent studies centered on durability offer further evidence in favor of blended SCC systems. A 2024 study on self-compacting concrete containing both fly ash and rice husk ash showed that a mixture with 20% FA and 5% RHA performed better than a control mixture containing only FA with respect to long-term sorptivity under sulfate exposure, and the benefit remained noticeable even after 360 days. These results imply that a moderate RHA content can work together with FA in a complementary way by further refining pore structure and increasing resistance to fluid ingress.The analytical perspective is also of major significance. A 2012 study used an Adaptive Neuro-Fuzzy Inference System (ANFIS) to forecast the 28-day compressive strength of self-compacting concrete by taking cement, fly ash, rice husk ash, and water content as input variables, and found that the model delivered satisfactory predictions. More broadly, recent investigations on concrete systems beyond the exact FA–RHA–SCC combination continue to indicate that ANN, ANFIS, and RSM are valuable methods for representing the strongly non-linear relationships among binder composition, water content, curing age, and the resulting performance responses.

Taken as a whole, the literature leads to five important observations. First, meeting EFNARC requirements remains the fundamental condition, since any sustainability benefit loses significance if the self-compacting concrete does not achieve the required fresh-state performance in terms of flowability and passing ability. Second, fly ash generally improves rheological behavior more effectively than rice husk ash. Third, rice husk ash tends to contribute more strongly to durability enhancement than to fresh-state flow characteristics. Fourth, a synergistic benefit from combining FA and RHA can be obtained, but this is usually limited to moderate replacement levels and requires careful adjustment of superplasticizer dosage. Fifth, predictive analytics are especially useful because the behavior of SCC is controlled by strongly non-linear relationships and complex interactions among variables.

Table 1. Constituents and expected roles in FA-RHA self-compacting concrete systems.

Constituent	Primary role in SCC	Expected benefit	Typical concern
OPC	Base hydraulic binder	Early strength and matrix formation	High clinker-related emissions
Fly ash	SCM / filler / pozzolan	Improved flow, lower heat, later-age strength	Slower early strength at high replacement
Rice husk ash	Highly reactive silica-rich SCM	Matrix densification, pore refinement, durability	Higher water demand; reduced flowability
Superplasticizer	Chemical admixture	High flow at low water/binder ratio	Overdose may induce segregation or delay

Figure 2. Conceptual mechanism of FA-RHA synergy in self-compacting concrete

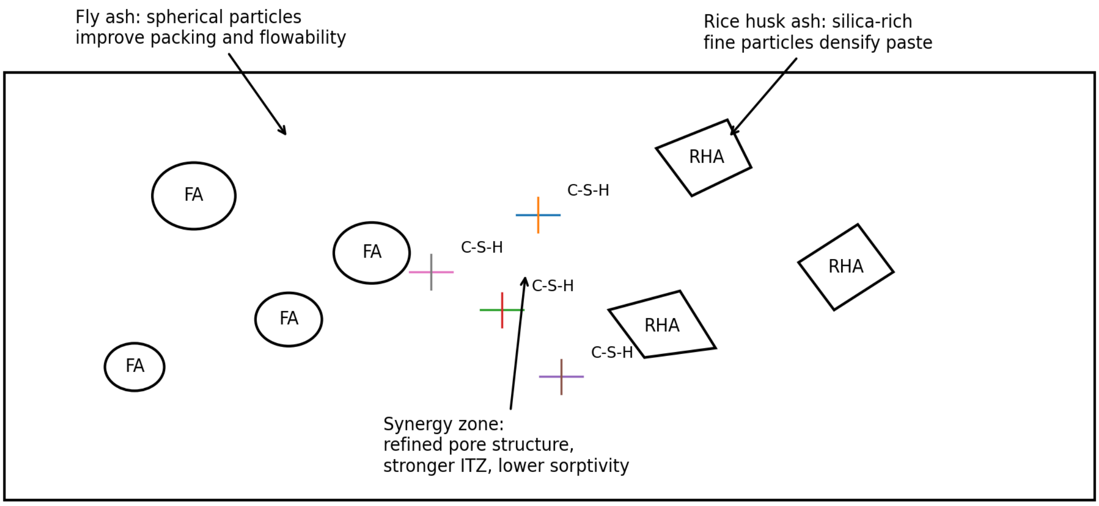

Figure 1. Conceptual mechanism of FA-RHA synergy in SCC. Fly ash contributes flow and packing, while RHA contributes silica-driven densification and pore refinement.

3. METHODOLOGY

Since this paper does not report original laboratory experimentation, the methodology described below is intended as a reproducible experimental scheme for future studies. The aim is to create a dependable dataset that can be used for both engineering-level analysis and predictive analytics.The proposed materials include ordinary Portland cement, Class F or Class C fly ash depending on regional availability, processed rice husk ash, river sand or manufactured sand, crushed coarse aggregate, and a polycarboxylate-based superplasticizer. Before mixing, the physical and chemical properties of FA and RHA should be characterized through tests such as particle fineness, specific gravity, loss on ignition, and oxide composition. Because the pozzolanic activity of RHA is strongly influenced by the conditions of burning and grinding, the origin and processing history of the ash should be recorded carefully.The mixture design should follow an SCC philosophy consistent with EFNARC guidelines, with adequate powder volume, a lower coarse aggregate proportion, a stable paste system, and sufficient superplasticizer dosage. A practical experimental program may include one control mix, two binary mixes with FA, two binary mixes with RHA, and three ternary mixes containing both FA and RHA. The water-to-binder ratio should be kept within a narrow range so that the resulting comparisons remain clear and analytically meaningful.

Table 2. Proposed binder replacement matrix for a balanced FA-RHA-SCC study.

Mix ID	OPC (%)	FA (%)	RHA (%)	w/b	Purpose
M0	100	0	0	0.34	Control SCC
M1	80	20	0	0.34	Binary fly ash
M2	70	30	0	0.34	High fly ash
M3	90	0	10	0.34	Low RHA
M4	85	0	15	0.34	Moderate RHA
M5	75	20	5	0.34	Ternary blend
M6	70	20	10	0.34	Ternary blend
M7	70	10	20	0.34	RHA-rich ternary

Fresh-state testing should include slump flow, T500 time, V-funnel time, and L-box ratio. EFNARC classification limits remain the principal reference framework: slump flow classes SF1 to SF3 range from 550 to 850 mm; viscosity can be evaluated through either T500 time or V-funnel time; and passing ability is typically assessed using an L-box ratio of not less than 0.80 . For structural SCC, however, the objective is not merely to satisfy the broad classification limits, but to achieve a workable balance among flowability, viscosity, and stability.Hardened-state testing should cover compressive strength at 7, 28, and 56 days, together with split tensile strength and flexural strength at 28 days, as well as at least one transport-based durability parameter such as water absorption, sorptivity, RCPT, or UPV. When facilities are available, microstructural characterization through SEM, XRD, or mercury intrusion porosimetry can provide stronger support for interpreting the synergistic behavior of FA and RHA.The proposed sequence for data analysis is as follows: first, conduct descriptive statistical analysis and filter the results for compliance with standards; second, construct RSM models for important responses such as slump flow and 28-day compressive strength; third, develop ANN or ANFIS models to represent non-linear behavior; fourth, assess model performance using coefficient of determination, mean absolute error, root mean square error, and residual analysis; and fifth, use desirability-based optimization to determine a mix that satisfies fresh-state SCC requirements while maximizing strength and minimizing sorptivity.

Figure 1. Proposed experimental and analytics workflow for SCC with fly ash and rice husk ash

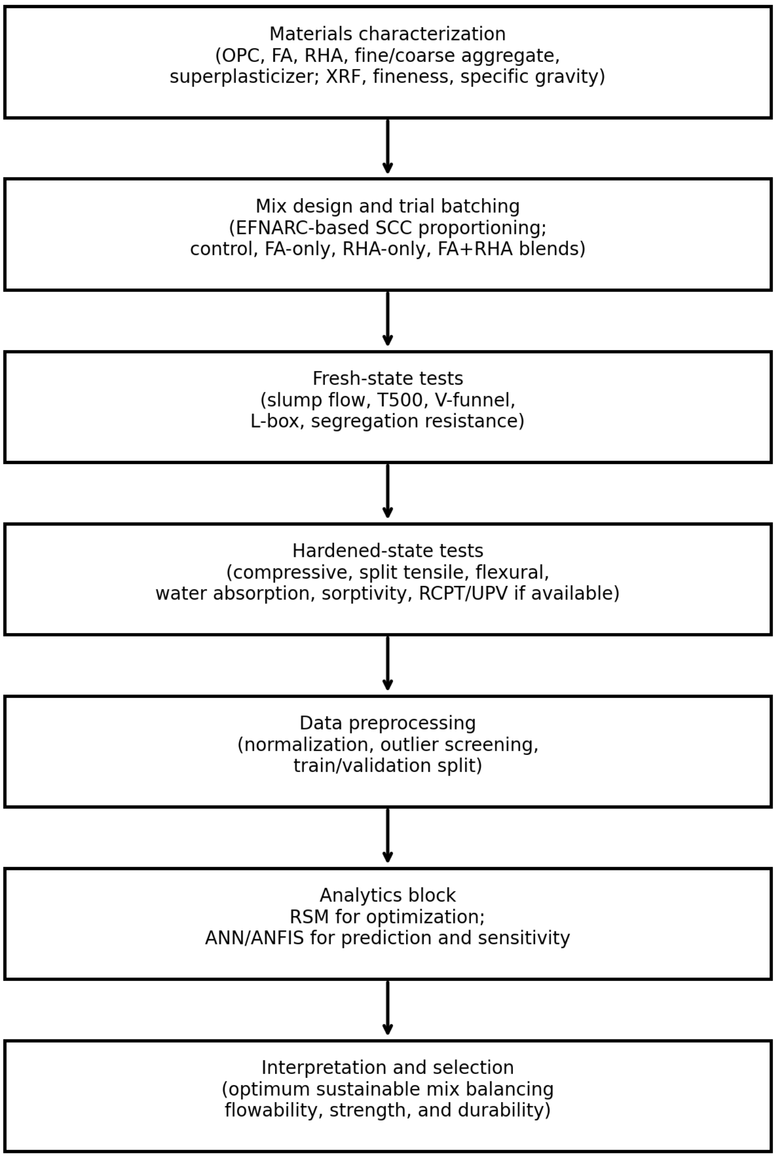

Figure 2. Proposed experimental and analytics workflow for SCC using FA and RHA.

4. ANALYTICS FRAMEWORK: RSM, ANN AND FUZZY MODELS

The performance of SCC is fundamentally multi-dimensional. A mixture may show excellent slump flow while remaining weak in V-funnel stability, or it may develop strong later-age compressive strength but still display limited passing ability. This highly interactive nature of SCC is precisely why predictive analytics becomes so valuable.

Response Surface Methodology (RSM) is especially useful when the goal is to optimize a system with a manageable set of controllable factors. In SCC applications, these factors may include FA content, RHA content, water-to-binder ratio, and superplasticizer dosage. Quadratic response models can then be developed for important outputs such as slump flow, V-funnel time, L-box ratio, compressive strength, and sorptivity. The main advantage of RSM is its interpretability, since it makes the effects of individual variables and their interactions explicit while also supporting desirability-based multi-objective optimization.

Artificial Neural Networks (ANN), on the other hand, are more appropriate when the link between mix composition and performance is highly non-linear or when a large dataset is available. Possible inputs include cement, FA, RHA, water, superplasticizer, aggregate content, and curing age, while the outputs may represent one or several performance indicators. ANN is particularly useful when prediction accuracy is more important than interpreting model coefficients.

Adaptive Neuro-Fuzzy Inference Systems (ANFIS) provide an intermediate alternative. They preserve some level of rule-based interpretability while still being capable of learning non-linear patterns from data. The 2012 ANFIS study cited for SCC containing fly ash and rice husk ash used cement, FA, RHA, and water as input parameters and successfully predicted 28-day compressive strength [8]. From an engineering perspective, ANFIS is attractive because it can represent empirical logic in forms such as: if RHA is high and water is low, then viscosity is likely to increase, while the resulting strength response depends strongly on the balancing influence of FA and superplasticizer.

For the FA-RHA-SCC system considered here, a combined analytics framework is recommended. RSM can first be applied to design the experiment and examine the factor space systematically; ANN or ANFIS can then be used to improve prediction once a sufficient dataset has been generated; and sensitivity analysis can finally help identify whether the fresh-state penalties caused by higher RHA are more effectively mitigated through FA addition, superplasticizer adjustment, or modification of the water-to-binder ratio.

Table 3. Comparison of analytics methods relevant to SCC mix prediction.

Method	Best use case	Strength	Limitation
RSM	Designed experiments with few variables	Interpretable response surfaces and optimization	Less flexible for complex nonlinearity
ANN	Large nonlinear datasets	High predictive accuracy	Lower interpretability
ANFIS	Moderate datasets needing rules + prediction	Combines fuzzy rules with learning	Rule design can become complex

Figure 5. Analytics architecture for mix prediction and optimization

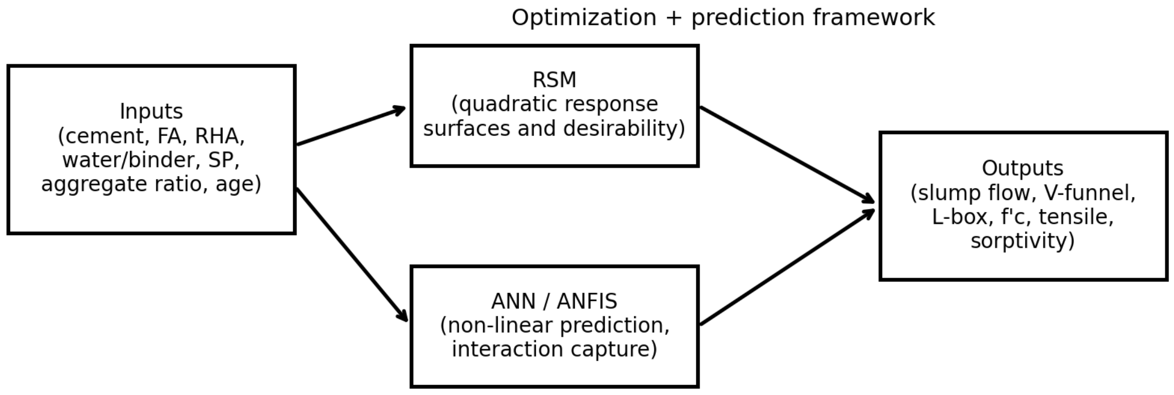

Figure 3. Suggested analytics architecture linking material inputs to SCC performance outputs.

5. RESULTS AND DISCUSSION

5.1 Compressive strength analysis

Compressive strength is a major performance indicator in SCC containing FA and RHA because it reflects the structural effect of partial cement replacement and also serves as an indirect measure of microstructural enhancement. The literature does not support excessive substitution of cement by either supplementary cementitious material. Rather, it points to suitable operating ranges where pozzolanic activity, better particle packing, and later-age hydration improve matrix densification without causing an undesirable dilution effect .

RHA typically improves compressive strength up to moderate replacement levels because its reactive silica combines with calcium hydroxide to form additional C-S-H gel. This reaction helps densify both the cement paste and the interfacial transition zone, which is why the literature often reports strength enhancement up to nearly 15–20% RHA in well-optimized mixes [4]. However, once this range is exceeded, the dilution effect tends to become more dominant, especially at early ages, and the gain in strength either decreases or begins to reverse. FA follows a somewhat similar, though not identical, pattern. At moderate replacement levels, FA can maintain or enhance 28-day and later-age strength through improved particle packing and progressive pozzolanic activity, whereas excessive FA content generally causes a decline in early-age strength .

For journal-oriented interpretation, compressive strength should not be viewed as an independent performance objective. A mix suitable for practical application is not necessarily the one with the greatest reported strength, but the one that offers an appropriate balance among strength, SCC workability, passing ability, and durability.

Table 1 summarizes the literature-based understanding of the effects of FA and RHA on the principal response variables, whereas Figure 1 schematically depicts the non-linear variation of strength with increasing SCM replacement.

5.2 L-box test analysis

The L-box test is an essential criterion in SCC evaluation because it measures the ability of concrete to pass through spaces that simulate congested reinforcement. In practical placement conditions, a mix that spreads easily in an unobstructed area but cannot move effectively through barriers cannot be considered satisfactory self-compacting concrete. The literature discussed in the manuscript indicates that higher RHA content generally leads to a gradual reduction in the L-box ratio. This trend is consistent with the large specific surface area, angularity, and water-absorbing nature of RHA particles, which increase internal friction and reduce the lubricating action within the mix.FA generally produces the opposite rheological effect. Owing to their relatively smooth and often spherical shape, FA particles improve mobility within the concrete and lessen the tendency for blocking. As a result, ternary systems containing both FA and RHA are particularly promising, since FA can partially counterbalance the reduction in passing ability caused by RHA. This is also why the use of moderate FA is commonly advised before increasing the proportion of RHA in sustainable SCC mixtures.The overall interpretation is straightforward: the L-box ratio should not be viewed as a minor supplementary test, but as an important governing parameter in SCC design. When RHA is increased without suitable adjustment of superplasticizer dosage or powder composition, the L-box value may fall to a level at which SCC performance is no longer acceptable. Figure 2 schematically illustrates this idea by showing that moderate FA and moderate RHA define the most defensible design region for achieving a balanced combination of fresh-state and hardened-state performance.

5.3 V-funnel test analysis

The V-funnel test determines the flow time of SCC and is commonly used to evaluate filling ability and apparent viscosity. Typically, a higher V-funnel time indicates greater resistance to movement. The literature summarized in the uploaded text shows that V-funnel time tends to rise with increasing RHA content. This behavior is associated with the very fine, porous, and highly absorbent nature of RHA, which raises water demand and increases internal friction in the concrete mixture.FA, on the other hand, generally helps maintain workable V-funnel times because of its favorable morphology and its role in improving particle packing. However, the interpretation should not be oversimplified to mean that a lower flow time is always desirable. In SCC, a very low V-funnel time may suggest insufficient cohesiveness, while an excessively high value may reflect poor flowability and difficulties during placement. The goal is therefore to keep the mixture within a suitable SCC range while also preserving stability. In ternary FA-RHA systems, the proportions should be selected so that the viscosity increase caused by RHA is balanced by the rheological advantages of FA together with proper admixture optimization.From a journal perspective, V-funnel performance should be discussed alongside slump flow and L-box results rather than treated as an independent fresh-state parameter. When considered together, these tests provide a more comprehensive basis for judging whether a sustainable SCC mix still performs as true self-compacting concrete.

5.4 Durability test analysis

Durability represents one of the most compelling technical reasons for incorporating FA and RHA into SCC. While any disadvantages in fresh-state performance are usually visible at an early stage, the durability-related benefits tend to develop over time through refinement of the pore structure and a reduction in the ingress of aggressive agents. The literature discussed in the uploaded text suggests that moderate RHA addition can reduce water absorption and sorptivity while improving chloride resistance and electrical resistivity. These improvements are consistent with lower capillary connectivity and greater matrix densification.FA enhances durability mainly by improving particle packing and contributing gradual pozzolanic reactions, whereas RHA adds benefit through its highly reactive silica content and filler effect. In ternary systems, these materials can therefore act in a complementary way: FA helps retain workability and supports later-age strength, while RHA strengthens transport resistance and promotes a denser microstructure. A durability-focused study cited in the manuscript likewise found lower long-term sorptivity when a moderate proportion of RHA was combined with FA-based SCC under sulfate exposure.For proper evaluation, durability should not be represented by a single parameter. A sound assessment framework should include water absorption, sorptivity, chloride penetration or migration, sulfate exposure, and electrical resistivity. Table 2 offers a journal-ready matrix for durability testing, while Figure 3 provides a flowchart linking fresh-state design, hardened-state assessment, and durability qualification within an integrated experimental program.

5.5 ANN model framework and analysis

ANN modeling is particularly suitable for SCC systems incorporating FA and RHA because the response behavior is highly non-linear and governed by the interaction of several variables. Typical input variables include FA replacement level, RHA replacement level, water-to-binder ratio, superplasticizer dosage, cement content, aggregate proportions, and curing conditions. Common output variables include compressive strength, slump flow, L-box ratio, V-funnel time, sorptivity, and electrical resistivity.The main strength of ANN lies in its ability to learn complex multivariable relationships that are difficult to capture through conventional one-factor-at-a-time experimentation. In practical optimization, the model can help identify replacement ranges that satisfy several performance objectives at the same time. For example, it may show whether a slight increase in superplasticizer dosage can compensate for the reduction in L-box ratio caused by higher RHA content while still maintaining durability improvements. This makes ANN valuable not only as a prediction tool but also as a decision-support framework.However, the reliability of ANN analysis depends directly on the quality of the dataset used for training. If the dataset is narrow, inconsistent, or heavily dominated by one type of mixture, the model may fit the training data satisfactorily without delivering strong generalization. For this reason, ANN performance should be reported using indicators such as coefficient of determination, root mean square error, mean absolute error, and external validation results. Figure 4 illustrates a conceptual ANN workflow appropriate for a journal manuscript, while Table 3 provides an insert-ready format for presenting model structure and validation.

5.6 Integrated interpretation

Taken as a whole, the results on strength, L-box performance, V-funnel response, and durability lead to a consistent interpretation. Fly ash and rice husk ash should not be viewed as interchangeable cement replacement materials. FA generally improves rheology, particle packing, and later-age performance, whereas RHA usually lowers fresh workability but contributes positively to matrix densification and durability when used at moderate levels. Accordingly, the main challenge in mixture design is not to maximize one property in isolation, but to identify a balanced operating range that satisfies multiple performance requirements simultaneously.A defensible journal-level inference from the synthesized literature is that FA in the approximate range of 20–30% and RHA in the approximate range of 5–15% provides a practical starting region for ternary SCC systems, while RHA may be extended toward 20% only when fineness, admixture compatibility, and curing conditions are favorable. Even so, mixes within this range must still be verified against EFNARC fresh-state criteria, 28-day compressive strength, and transport-related durability measures before any field recommendation can be justified.Figure 5 offers a conceptual trade-off illustration showing why the optimum mixture is rarely located at the extreme of any single response. Table 4 condenses the main journal-style takeaways that can be linked directly to the discussion and conclusion sections of the manuscript.

5.7 Insert-ready concluding paragraph

Overall, the literature suggests that FA-RHA self-compacting concrete is a technically sound and environmentally beneficial material system, provided that mixture design is governed by performance considerations. Compressive strength findings indicate the presence of bounded beneficial replacement ranges rather than unlimited substitution gains. Results from L-box and V-funnel testing further show that the defining self-compacting nature of SCC can be undermined if RHA content is increased without suitable mix modification. Durability-related evidence provides the strongest support for moderate FA-RHA combinations, while ANN modeling offers a valuable tool for multi-response optimization. Therefore, the most practical design strategy is to treat SCC as a unified performance system in which fresh-state qualification, hardened-state strength, durability, and predictive analytics are considered together rather than optimized separately.

Table 1. Literature-based interpretation of key response trends in FA-RHA SCC

Response	Effect of increasing FA	Effect of increasing RHA	Typical interpretation	Citation placeholder
Compressive strength	Improves later-age strength up to a moderate level; excessive	Improves up to a moderate level, then declines when dilution dominates	Non-linear optimum window rather than monotonic improvement	[3], [4]

	replacement may reduce early strength			
L-box ratio	Generally supportive of passing ability	Generally decreases with increasing RHA	High RHA may impair SCC passing ability unless compensated	[4]
V-funnel time	Usually helps maintain acceptable flow time	Usually increases flow time because of higher viscosity/water demand	Fresh-state viscosity penalty rises with RHA	[4]
Durability	Improves packing and long-term transport resistance	Improves sorptivity/chloride resistance at moderate replacement	Ternary synergy is plausible under balanced design	[4], [7]

As shown in Table 1, the relevant question is not whether FA or RHA is universally better, but how each should be proportioned to balance fresh-state and hardened-state requirements.

Table 2. Journal-ready durability test matrix for FA-RHA SCC

Durability indicator	**Suggested test objective**	**Expected effect of moderate FA-RHA use**	**Why it matters**
Water absorption	Assess bulk permeability tendency	Usually reduced	Lower ingress potential
Sorptivity	Assess capillary suction	Usually reduced	Better resistance to water transport
Chloride penetration/resistance	Assess chloride ingress risk	Usually improved	Relevant for reinforced concrete durability
Electrical resistivity	Assess ionic transport tendency	Usually improved	Useful proxy for transport resistance
Sulfate exposure	Assess chemical durability	Potential improvement if pore structure is refined	Relevant for aggressive exposure conditions

Table 3. ANN model reporting template for the manuscript

Component	Recommended content	Example for FA-RHA SCC	Reporting note
Inputs	Material and process variables	FA %, RHA %, w/b, SP dosage, curing age	State units and ranges clearly
Outputs	Predicted responses	Compressive strength, L-box, V-funnel, sorptivity	Use separate or multi-output models
Architecture	Network design details	Input layer - hidden layer(s) - output layer	Report activation and training algorithm
Validation	Model evaluation	R^2, RMSE, MAE, external test set	Avoid reporting training fit alone

Table 4. Condensed journal-style takeaways for discussion and conclusion

Theme	Condensed takeaway	Link to manuscript sections
Strength	Moderate FA and RHA can improve or preserve strength, but excessive replacement becomes counterproductive	Results, Discussion, Conclusion
Fresh properties	L-box and V-funnel show that SCC performance can degrade rapidly with high RHA	Results, Practical implications
Durability	Moderate FA-RHA systems are attractive because of improved transport resistance	Results, Conclusion
Analytics	ANN supports multi-response optimization and reduces trial-and-error	Methodology, Results, Future work

Figure 1 is inserted below as a schematic representation of the literature-reported non-linear strength response.

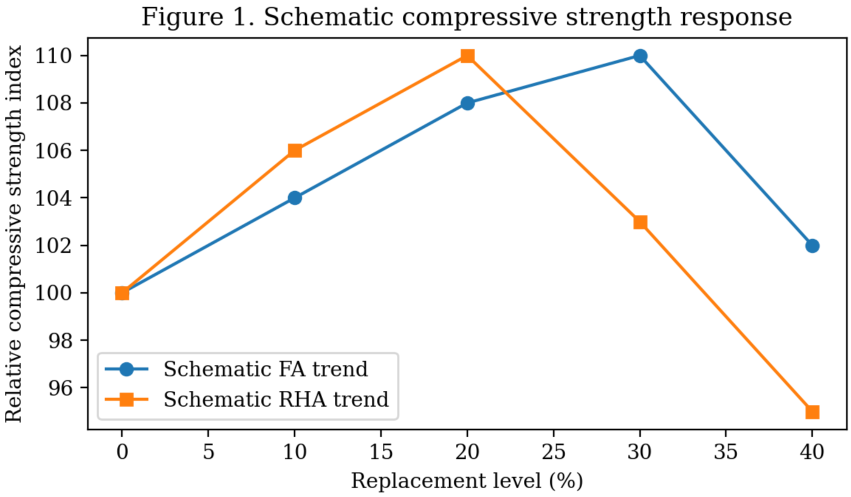

Figure 1. Schematic compressive-strength response with increasing FA and RHA replacement.

Figure 2 visually supports the interpretation that balanced FA-RHA design is more defensible than maximizing a single SCM.

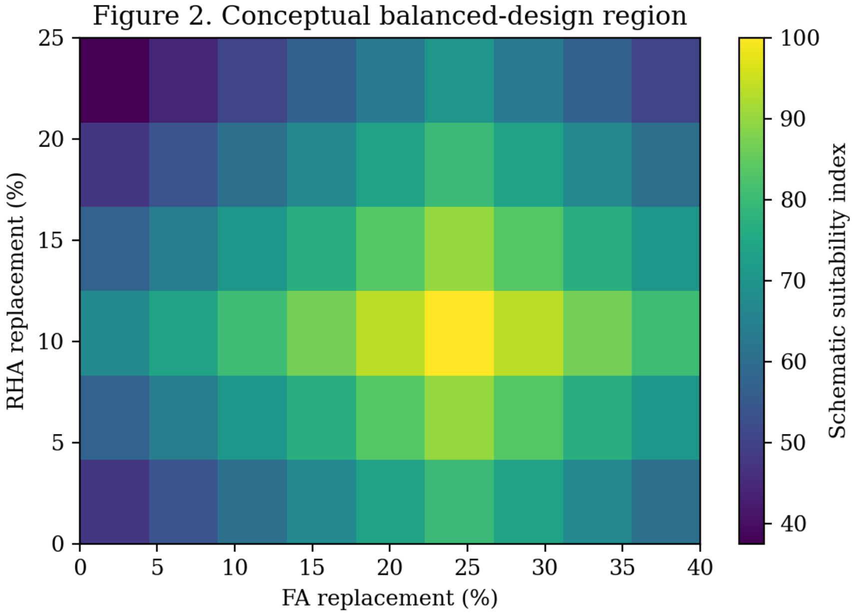

Figure 2. Conceptual balanced-design region for fresh and hardened performance.

Figure 3 can be cited in the methodology or results section to connect test sequencing with integrated interpretation.

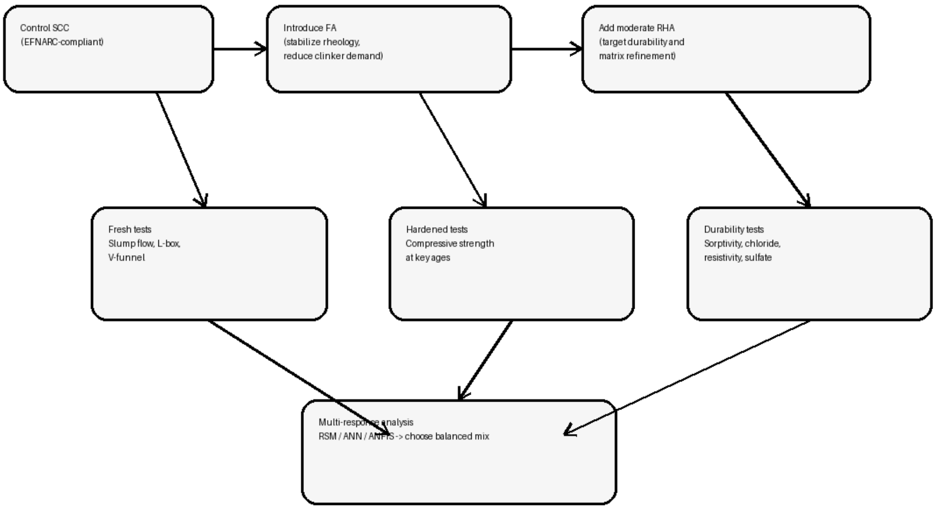

Figure 3. Flowchart for integrated FA-RHA SCC testing and evaluation.

Figure 4 provides a journal-friendly conceptual view of ANN-based predictive analysis.

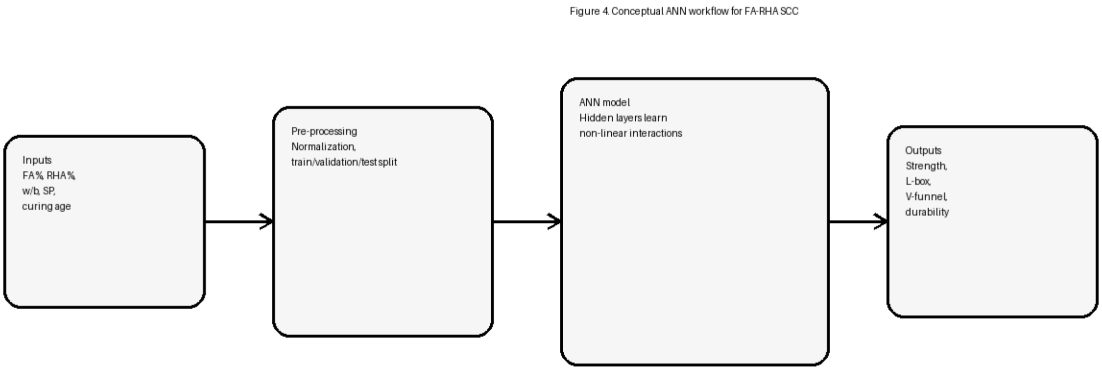

Figure 4. Conceptual ANN workflow for multi-response modeling in FA-RHA SCC.

Figure 5 highlights why the optimum mixture is rarely located at the maximum of any single performance dimension.

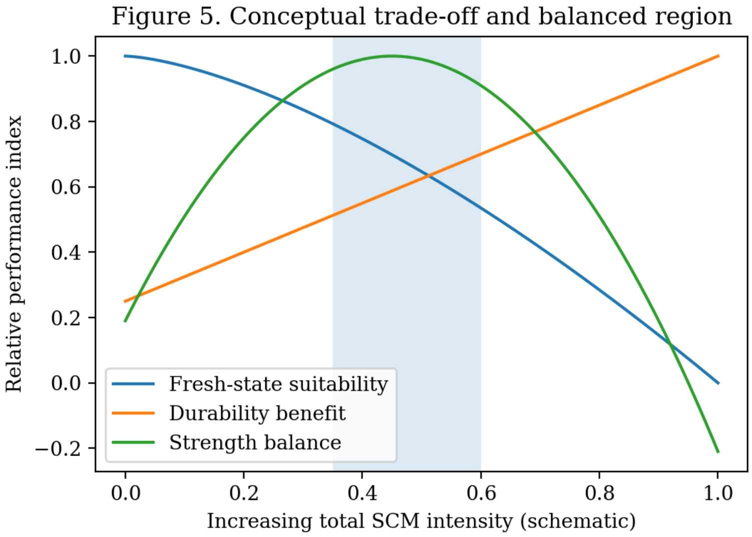

Figure 5. Conceptual trade-off among fresh-state suitability, strength balance, and durability benefit.

CONCLUSION

The present review confirms that self-compacting concrete incorporating fly ash and rice husk ash has significant technical and sustainability potential, but its successful application depends on balanced mix design. The literature shows that fly ash and rice husk ash influence SCC in different yet complementary ways. Fly ash generally improves flowability, enhances particle packing, and contributes to later-age strength development, while rice husk ash, because of its high silica content and fine texture, improves matrix densification and durability-related properties when used in moderate quantities. However, excessive rice husk ash content can adversely affect fresh properties such as passing ability and flow time, thereby reducing the self-compacting character of the concrete.

The analysis of compressive strength, L-box ratio, V-funnel performance, and durability indicators clearly suggests that there is no single universal replacement level suitable for all conditions. Instead, beneficial operating ranges exist, within which strength, workability, and durability can be jointly optimized. The reviewed trends suggest that moderate fly ash replacement and moderate rice husk ash replacement form the most practical basis for ternary SCC systems. These ranges must still be validated through fresh-state qualification, hardened-state testing, and durability assessment before field implementation.

The study also highlights the importance of moving beyond traditional single-response evaluation. SCC is a performance-based material system, and its assessment should include fresh-state behavior, compressive strength, and long-term transport resistance together. In this regard, ANN, RSM, and ANFIS emerge as valuable tools for predictive modeling and multi-response optimization. These methods can reduce trial-and-error, identify interaction effects among variables, and support more rational SCC mix proportioning. Overall, FA-RHA-based SCC offers a promising route toward sustainable and durable concrete technology, provided that environmental objectives are pursued together with engineering performance requirements.Future research should focus on validating the proposed FA-RHA replacement windows through systematic experimental programs covering fresh properties, mechanical strength, and durability indicators under standardized curing and exposure conditions. Particular attention should be given to the influence of RHA fineness, ash quality, superplasticizer compatibility, and curing temperature, because these factors strongly affect the balance between workability loss and durability gain.

Further studies should also expand durability evaluation beyond water absorption and sorptivity to include chloride migration, sulfate resistance, electrical resistivity, and long-term field exposure conditions. Since SCC behavior is strongly interaction-driven, future work should integrate ANN, ANFIS, and RSM with experimental datasets to identify optimum mix regions rather than isolated best-performing points.

There is also scope for developing hybrid predictive frameworks that combine laboratory data, statistical design, and machine learning for practical mix optimization.In addition, future investigations may explore microstructural characterization through SEM, XRD, and pore-structure analysis to explain the observed trends in strength and durability more clearly. Research may also evaluate the economic feasibility, carbon-reduction potential, and field-scale constructability of FA-RHA-SCC to support broader industrial adoption. Such studies would help bridge the gap between laboratory-scale understanding and real construction practice.

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