



Elevated-Temperature Behaviour and Residual Compressive Strength of Rice Husk Ash-Blended Concrete Incorporating Superabsorbent Polymer

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ABSTRACT

The deterioration of concrete under elevated temperatures poses significant challenges to structural safety and post-fire rehabilitation, highlighting the need for sustainable cementitious materials with improved residual mechanical performance. This study investigated the effects of rice husk ash (RHA) and superabsorbent polymer (SAP) on the residual compressive strength of Portland limestone cement (PLC) concrete exposed to elevated temperatures. PLC was partially replaced with RHA at 10, 15, 20 and 25%, while SAP dosages ranged from 0.1 to 0.5%. Compressive strength was evaluated before and after exposure to 200, 400 and 600°C, using conventional PLC concrete as the control. Results showed progressive strength reduction with increasing temperature across all mixtures. However, RHA-SAP incorporation generally improved residual-strength retention, with 0.3% SAP producing the highest absolute residual strength at each RHA replacement level. At 600°C, mixtures containing 10, 15, 20 and 25% RHA with 0.3% SAP retained 75.7, 81.3, 74.5 and 70.5% of their initial strengths, respectively, compared with 63.9% for the control. The optimum mixture, comprising 15% RHA and 0.3% SAP, recorded an initial compressive strength of 34.2 MPa and a residual strength of 27.8 MPa at 600°C, representing approximately 52.7% higher residual strength than the control (18.2 MPa). The improvement may be associated with pozzolanic matrix refinement and SAP-assisted internal curing. The findings identify 15% RHA and 0.3% SAP as the most favourable combination within the investigated mixtures, demonstrating the potential for reducing PLC consumption while improving residual compressive-strength performance following elevated-temperature exposure.

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INTRODUCTION

Concrete is widely used in construction due to its versatility, durability, affordability and high compressive strength. However, exposure to elevated temperatures, particularly during fire incidents, can significantly impair its mechanical performance through moisture loss, dehydration of cement hydration products, differential thermal expansion and microcrack formation. These processes weaken the cementitious matrix and reduce its residual load-bearing capacity.

Shahraki *et al.* (2023) reported that elevated temperatures considerably affect the residual compressive strength of concrete, with deterioration influenced by material composition, aggregate characteristics and heating conditions. Consequently, enhancing the post-heating mechanical performance of concrete remains important for structural safety and rehabilitation.

The increasing demand for sustainable construction materials has encouraged the use of supplementary cementitious materials to reduce

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conventional cement consumption and its associated environmental impacts. Rice husk ash (RHA), an agricultural by-product containing reactive silica when appropriately processed, has demonstrated potential as a partial cement replacement. Its pozzolanic reaction with calcium hydroxide produces additional calcium silicate hydrate (C-S-H), contributing to matrix densification and mechanical strength development. Endale *et al.* (2023) emphasized that RHA performance depends on its chemical composition, fineness, processing conditions and replacement level. Similarly, Nduka *et al.* (2022) investigated the mechanical and microstructural characteristics of RHA-blended concrete internally cured with SAP, highlighting the potential benefits of combining pozzolanic materials with internal-curing agents. Nevertheless, excessive RHA replacement may increase cement dilution and reduce the formation of strength-contributing hydration products.

Superabsorbent polymers (SAPs) are increasingly utilized as internal-curing admixtures because of their capacity to absorb, retain and gradually release water during cement hydration. This mechanism supports continued hydration and may promote microstructural development, particularly in blended cementitious systems. Mechtcherine *et al.* (2021) reported that SAP incorporation influences hydration, pore structure and mechanical properties, while Zhou *et al.* (2024) emphasized the importance of water absorption and release behaviour in determining concrete performance. However, SAP effectiveness depends on dosage, as excessive incorporation may generate residual pores that weaken the hardened matrix. Under elevated-temperature exposure, SAP-induced pores may also influence moisture redistribution and vapour transport, although excessive porosity can adversely affect residual mechanical strength.

The combined incorporation of RHA and SAP presents a potential approach to developing sustainable concrete with improved post-heating mechanical performance through complementary pozzolanic and internal-curing mechanisms. Although previous studies have investigated their influence on hydration, mechanical properties and

microstructure (Mechtcherine *et al.*, 2021; Nduka *et al.*, 2022), further systematic investigation is required to understand how varying RHA replacement levels and SAP dosages jointly influence residual compressive strength following elevated-temperature exposure. Establishing these relationships is essential for identifying mixture proportions that balance cement reduction, hydration development and resistance to thermal deterioration.

Therefore, this study investigated the residual compressive strength of Portland limestone cement (PLC) concrete incorporating 10, 15, 20 and 25% RHA as partial cement replacements and SAP dosages ranging from 0.1 to 0.5%. Compressive strength was evaluated under unheated conditions and following exposure to 200, 400 and 600°C. The study aimed to assess the influence of RHA and SAP proportions on residual-strength retention, identify the most favourable mixture composition and evaluate the potential of RHA-SAP concrete for sustainable construction applications requiring improved post-heating mechanical performance.

MATERIALS AND METHOD

This section describes the materials, mix proportions, specimen preparation and experimental procedures adopted to evaluate the elevated-temperature performance of RHA-SAP blended cement concrete. The methodology involved partial replacement of PLC with RHA at varying proportions, incorporation of SAP at different dosages, and assessment of residual compressive strength following exposure to 200, 400 and 600°C.

Materials

The materials used in this study comprised Portland limestone cement (PLC), rice husk ash (RHA), superabsorbent polymer (SAP), fine aggregate, coarse aggregate and potable water as shown in Plate 1. PLC served as the primary binding material, while RHA was incorporated as a supplementary cementitious material through partial replacement of PLC. SAP was introduced as an internal-curing admixture to investigate its influence on the residual

compressive strength of concrete subjected to elevated temperatures.



Plate 1: Pictorial view of material used

RHA was sourced from Hillcrest Rice Mill, Amberi along Ajase-Ipo-Offa Road, Kwara State (Lat: 8°14'45.1392"N, Long: 4°32'29.6916"E) at a temperature of 600°C. SAP was purchased from Safideb Chemicals in Osogbo, Osun State, Nigeria. Portland Limestone Cement (PLC), Dangote 3X, classified as CEM II/A-L 42.5R, was obtained from a local supplier within Sango-Ota, Ogun State, Nigeria. Fine and coarse aggregates were obtained in Sango-Ota, Ogun State, Nigeria. Potable water was sourced from the Nigerian Building and Road Research Institute (NBRRI), Sango-Ota, Ogun State, where the research was carried out.

Experimental Design and Mix Proportions

The experimental programme was designed to evaluate the combined effects of RHA replacement level and SAP dosage on the elevated-temperature performance of PLC concrete. PLC was partially replaced with RHA at

10, 15, 20 and 25%, while SAP was incorporated at dosages of 0.1, 0.2, 0.3, 0.4 and 0.5%. Conventional concrete containing 100% PLC without SAP was designated as Control 1. For each RHA replacement level, a corresponding mixture without SAP served as Control 2, providing a reference for evaluating the contribution of SAP.

The mixtures were tested for compressive strength under unheated conditions and after exposure to 200, 400 and 600°C. This arrangement allowed the effects of temperature, RHA replacement, and SAP dosage to be evaluated individually and comparatively. The selected temperature levels represented progressively more severe thermal exposure conditions relevant to assessing residual concrete strength. The concrete mixtures were prepared using a 1:2:4 mix proportion with a water-to-binder ratio of 0.5. The mixture proportions and material quantities are presented in Table 1.

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Table 1: Batching of Material for Production of Concrete Specimen

Sample ID	Mixture Description	PLC (kg)	RHA (kg)	SAP (g)
M0	100% PLC (Primary Control)	50	0	0
M10	90% PLC + 10% RHA	45	5	0
M10A	90% PLC + 10% RHA + 0.1% SAP	45	5	50
M10B	90% PLC + 10% RHA + 0.2% SAP	45	5	100
M10C	90% PLC + 10% RHA + 0.3% SAP	45	5	150
M10D	90% PLC + 10% RHA + 0.4% SAP	45	5	200
M10E	90% PLC + 10% RHA + 0.5% SAP	45	5	250
M15	85% PLC + 15% RHA	42.5	7.5	0
M15A	85% PLC + 15% RHA + 0.1% SAP	42.5	7.5	50
M15B	85% PLC + 15% RHA + 0.2% SAP	42.5	7.5	100
M15C	85% PLC + 15% RHA + 0.3% SAP	42.5	7.5	150
M15D	85% PLC + 15% RHA + 0.4% SAP	42.5	7.5	200
M15E	85% PLC + 15% RHA + 0.5% SAP	42.5	7.5	250
M20	80% PLC + 20% RHA	40	10	0
M20A	80% PLC + 20% RHA + 0.1% SAP	40	10	50
M20B	80% PLC + 20% RHA + 0.2% SAP	40	10	100
M20C	80% PLC + 20% RHA + 0.3% SAP	40	10	150
M20D	80% PLC + 20% RHA + 0.4% SAP	40	10	200
M20E	80% PLC + 20% RHA + 0.5% SAP	40	10	250
M25	75% PLC + 25% RHA	37.5	12.5	0
M25A	75% PLC + 25% RHA + 0.1% SAP	37.5	12.5	50
M25B	75% PLC + 25% RHA + 0.2% SAP	37.5	12.5	100
M25C	75% PLC + 25% RHA + 0.3% SAP	37.5	12.5	150
M25D	75% PLC + 25% RHA + 0.4% SAP	37.5	12.5	200
M25E	75% PLC + 25% RHA + 0.5% SAP	37.5	12.5	250

Preparation and Curing of Concrete Specimens

Concrete specimens were prepared according to the prescribed mix proportions. The constituent materials were batched and mixed to obtain a uniform concrete mixture. Fresh concrete was cast into 100 × 100 × 100 mm cube moulds, after which the specimens were demoulded and cured for 28 days before elevated-temperature exposure.

Elevated-Temperature Exposure Procedure

Following 28 days of curing, the concrete cube specimens were subjected to elevated temperatures of 200, 400 and 600 °C using an enclosed blower-assisted heating furnace at national laboratory complex, Nigerian Building and Road Research Institute, Km 10, Idiroko road, Ota, Ogun State. The furnace was heated to each specified target temperature, after which the specimens were maintained under the corresponding thermal condition for 60 minutes. Upon completion of the heating period, the

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specimens were allowed to cool for 24 hours before compressive-strength testing. Unheated specimens served as reference samples for evaluating residual compressive-strength retention and the extent of thermal deterioration.

Compressive-Strength Testing

The compressive strengths of the concrete specimens were determined using Universal Testing Machine of Control model with 2000kN capacity. Testing was carried out on the unheated reference specimens and on specimens previously exposed to temperatures of 200, 400 and 600°C. Each specimen was positioned centrally within the compression-testing machine and subjected to a continuously applied load until failure occurred. The maximum failure load was recorded and used to determine the compressive strength according to Equation (1):

$$C = \frac{P}{A} \quad 1$$

where:

C = compressive strength (MPa);

P = maximum applied load at failure (N);

A = loaded cross-sectional area of the specimen (mm²).

The compressive strength obtained after elevated-temperature exposure was designated as the residual compressive strength. The results were compared with the corresponding unheated compressive strengths to determine the extent of thermal deterioration.

Determination of Residual Compressive-Strength Retention

Residual compressive-strength retention was determined as the ratio of the compressive strength recorded after elevated-temperature exposure to the corresponding unheated compressive strength, expressed as a percentage.

The residual-strength retention was calculated using Equation (2):

$$RSR(\%) = \frac{C_{(heated)}}{C_{(unheated)}} \times 100 \quad 2$$

where:

RSR = residual compressive-strength retention (%);

C_(heated) = compressive strength after exposure to temperature (T) (MPa);

C_(unheated) = corresponding unheated compressive strength (MPa).

RESULTS AND DISCUSSION

This section presents and discusses the residual compressive strength of RHA-SAP blended cement concrete subjected to elevated temperatures. The results were compared with conventional Portland limestone cement (PLC) concrete to evaluate thermal strength deterioration and the combined influence of RHA and SAP on residual-strength retention. Generally, compressive strength decreased progressively with increasing exposure temperature across all mixtures.

The conventional PLC concrete recorded an initial compressive strength of 28.5 MPa, which declined to 26.8, 23.5 and 18.2 MPa after exposure to 200, 400 and 600°C, respectively, corresponding to 63.9% strength retention at 600°C. This deterioration may be attributed to moisture loss, dehydration of cement hydration products and thermally induced microcracking. Although RHA and SAP incorporation influenced the magnitude of strength reduction, none of the mixtures completely resisted thermal deterioration. The effects of varying RHA replacement levels and SAP dosages on residual compressive strength are discussed in the subsequent subsections.

Performance of Concrete at 10% RHA

At 10% RHA replacement, compressive strength decreased progressively with increasing exposure temperature from 200°C to 600°C, as shown in Figure 1. This reduction may be attributed to moisture loss, dehydration of cement hydration products, differential thermal expansion and thermally induced microcracking, consistent with the findings of Makinta *et al.* (2021). The conventional PLC concrete (Control 1) exhibited an initial compressive strength of 28.5 MPa, which declined to 26.8, 23.5 and 18.2 MPa at 200, 400 and 600°C, respectively, corresponding to 63.9%

strength retention at 600°C. In comparison, mixtures containing 10% RHA generally exhibited improved residual-strength retention, indicating the beneficial influence of partial cement replacement under elevated-temperature exposure.

The incorporation of SAP further enhanced residual compressive strength up to an optimum dosage of 0.3%. At 0.1% and 0.2% SAP, strength retention at 600°C increased to 72.5% and 73.7%, respectively, while the 0.3% SAP mixture achieved the highest retention of 75.7%, with compressive strength decreasing from 32.5 MPa under unheated conditions to 31.0, 28.8 and 24.6 MPa at 200, 400 and 600°C, respectively. This improvement may be associated with RHA-induced pozzolanic matrix refinement and SAP-assisted internal curing, which supports hydration and modifies pore structure (Mechtcherine *et al.*, 2021). Furthermore, SAP-generated pores may facilitate moisture redistribution during heating, potentially reducing internal vapour pressure, as

suggested by Hasholt *et al.* (2014), although this mechanism was not directly investigated in the present study.

Beyond 0.3% SAP, residual-strength retention declined to 73.4% and 72.1% at 0.4% and 0.5% SAP, respectively, suggesting that excessive SAP-induced porosity may counteract the benefits of internal curing (Zhao *et al.*, 2022). Nevertheless, these values remained higher than the 63.9% recorded for the PLC control. Overall, the 10% RHA-0.3% SAP mixture demonstrated the most favourable elevated-temperature performance within this series, retaining 24.6 MPa at 600°C compared with 18.2 MPa for conventional PLC concrete. This represents approximately 35.2% higher residual compressive strength and suggests potential benefits for concrete applications requiring improved post-heating mechanical performance. However, further structural-scale investigations are required to establish its suitability for fire-resistant construction

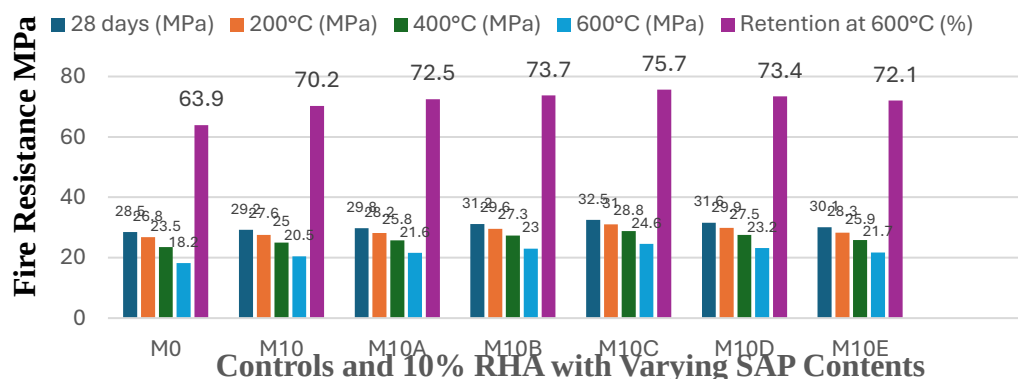


Figure 1: Compressive strength and residual-strength retention of concrete containing 10% RHA at different SAP dosages

Performance of Concrete with 15% RHA

At 15% RHA replacement, compressive strength decreased progressively with increasing exposure temperature from 200°C to 600°C, as illustrated in Figure 2. This deterioration may be attributed to moisture evaporation, dehydration of cement hydration products, differential thermal expansion and thermally induced microcracking, consistent with the findings of Ang'ang'o *et al.* (2024). Nevertheless, the 15% RHA mixtures

(M15-M15E) exhibited the most favourable elevated-temperature performance among the RHA replacement levels investigated, suggesting an appropriate balance between the filler and pozzolanic effects of RHA and cement dilution. Nduka *et al.* (2022) similarly highlighted the contribution of RHA to cementitious matrix development through pozzolanic reactions and additional calcium silicate hydrate (C-S-H) formation.

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SAP incorporation improved residual compressive strength compared with the M15, with the highest performance recorded at M15C. At M15A and M15B, the mixtures retained 75.6% and 77.0% of their initial compressive strengths at 600°C, respectively. The best-performing mixture, M15C, recorded an initial compressive strength of 34.2 MPa and residual strengths of 33.1, 31.2 and 27.8 MPa at 200, 400 and 600°C, respectively. This corresponds to 81.3% strength retention at 600°C, compared with 63.9% for conventional PLC concrete (M0). Furthermore, the residual compressive strength of M15C at 600°C was approximately 52.7% higher than that of M0 (18.2 MPa). This improvement may be associated with the complementary effects of RHA-induced matrix refinement and SAP-assisted internal curing, which promote hydration and microstructural development (Nduka *et al.*, 2022). Additionally, SAP-generated pores may facilitate moisture redistribution during heating, potentially reducing

internal vapour pressure (Lura and Terrasi, 2014), although this mechanism was not directly evaluated in the present investigation.

Increasing SAP dosage beyond 0.3% reduced residual-strength performance, with retention decreasing to 76.1% for M15D and 73.9% for M15E. This decline may be associated with excessive SAP-induced porosity, which weakens the hardened matrix and counteracts the benefits of internal curing. Comparison across RHA replacement levels further revealed that mixtures containing 0.3% SAP (M10C, M15C, M20C and M25C) retained 75.7%, 81.3%, 74.5% and 70.5% of their initial strengths at 600°C, respectively. The superior performance of M15C suggests a favourable balance between pozzolanic activity, internal curing and cement replacement, whereas higher RHA contents may increase cement dilution and limit the formation of strength-contributing hydration products.

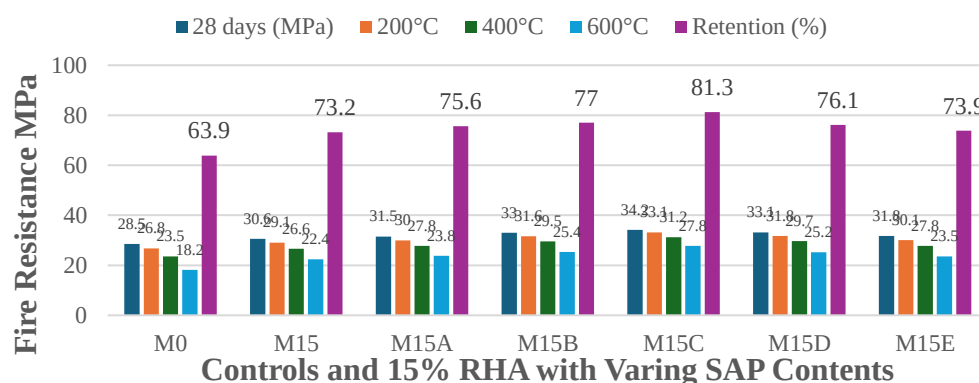


Figure 2: Compressive strength and residual-strength retention of concrete containing 15% RHA at different SAP dosages

Performance of Concrete with 20% RHA

At 20% RHA replacement, compressive strength decreased progressively with increasing exposure temperature from 200°C to 600°C, as illustrated in Figure 3. This deterioration may be attributed to moisture loss, dehydration of cement hydration products, differential thermal expansion and thermally induced microcracking, consistent with Ang'ang'o *et al.* (2024). Although the 20% RHA mixtures (M20-M20E) generally exhibited higher residual-strength retention than

conventional PLC concrete (M0), their performance was inferior to the corresponding 15% RHA mixtures, suggesting that increased cement dilution partly offset the beneficial filler and pozzolanic effects of RHA.

SAP incorporation improved residual-strength performance relative to the RHA-only control (M20), with the most favourable results obtained at 0.3% SAP. At 600°C, M20A and M20B retained 73.0% and 74.2% of their initial strengths, respectively, while M20C achieved the highest retention of 74.5%. M20C recorded an initial

compressive strength of 32.6 MPa, which decreased to 31.0, 28.5 and 24.3 MPa at 200, 400 and 600°C, respectively. Its residual strength at 600°C was approximately 33.5% higher than that of M0 (18.2 MPa). The improvement may be associated with RHA-induced matrix refinement and SAP-assisted internal curing, while SAP-generated pores could facilitate moisture redistribution during heating (Lura and Terrasi (2014). However, the latter mechanism was not directly verified in this study.

Beyond 0.3% SAP, strength retention declined to 73.4% for M20D and 71.2% for M20E, potentially due to excessive SAP-induced porosity

and reduced matrix continuity. Furthermore, M20C exhibited lower retention than M15C (81.3%), indicating that increasing RHA replacement beyond 15% reduced the beneficial effects of the combined RHA-SAP system. Nevertheless, M20C retained 24.3 MPa at 600°C, demonstrating the potential of 20% RHA replacement to reduce PLC consumption while maintaining improved post-heating mechanical performance relative to conventional concrete. Further structural-scale investigations are required to establish its suitability for fire-resistant applications.

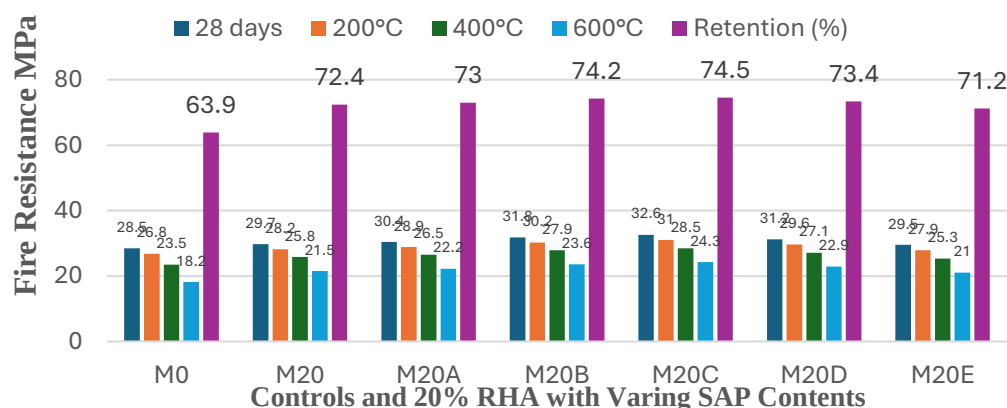


Figure 3: Compressive strength and residual-strength retention of concrete containing 20% RHA at different SAP dosages

Performance of Concrete with 25% RHA

At 25% RHA replacement, compressive strength decreased progressively with increasing exposure temperature from 200°C to 600°C, as illustrated in Figure 4. The reduction was relatively moderate at 200°C but became more pronounced at higher temperatures, potentially due to moisture loss, dehydration of cement hydration products, differential thermal expansion and thermally induced microcracking. Compared with the lower RHA replacement levels, the 25% RHA mixtures (M25-M25E) generally exhibited reduced residual-strength performance, suggesting that increased cement dilution partly offset the beneficial filler and pozzolanic effects of RHA. The reduced PLC content may have limited the availability of calcium hydroxide for secondary calcium silicate hydrate

(C-S-H) formation, thereby affecting matrix development and resistance to thermal deterioration.

The incorporation of SAP improved residual compressive strength relative to the RHA-only control (M25), with the highest absolute residual strength obtained at 0.3% SAP. The mixture M25C recorded an initial compressive strength of 30.5 MPa, which decreased to 28.8, 26.0 and 21.5 MPa following exposure to 200, 400 and 600°C, respectively. This corresponds to 70.5% strength retention at 600°C, compared with 63.9% for conventional PLC concrete (M0). The improvement may be associated with SAP-assisted internal curing and RHA-induced pozzolanic activity, which potentially enhance hydration and matrix development. Additionally, SAP-generated pores may facilitate moisture

redistribution during heating, as suggested by Ang'ang'o *et al.* (2024), although this mechanism was not directly verified in the present study.

At lower SAP dosages, M25A and M25B recorded residual-strength retention of 71.0% and 71.1%, respectively, at 600°C. Notably, M25B exhibited slightly higher percentage retention than M25C (70.5%), despite recording a lower absolute residual compressive strength of 21.2 MPa compared with 21.5 MPa for M25C. Increasing SAP dosage beyond 0.3% reduced residual-strength performance, with retention declining to 69.2% for M25D and 68.3% for M25E, potentially due to increased residual porosity and reduced matrix continuity. These findings indicate that M25C achieved the highest absolute residual compressive strength, whereas M25B provided

the greatest percentage strength retention within the 25% RHA series.

Overall, M25C recorded approximately 18.1% higher residual compressive strength at 600°C than M0 (18.2 MPa), although its performance remained below that of M15C, which recorded 27.8 MPa. Nevertheless, 25% RHA replacement offers greater PLC substitution while maintaining improved residual mechanical performance relative to conventional concrete. This suggests potential for sustainable concrete applications where cement reduction and post-heating strength retention are important considerations. However, further structural-scale investigations are necessary to establish its suitability for fire-resistant applications.

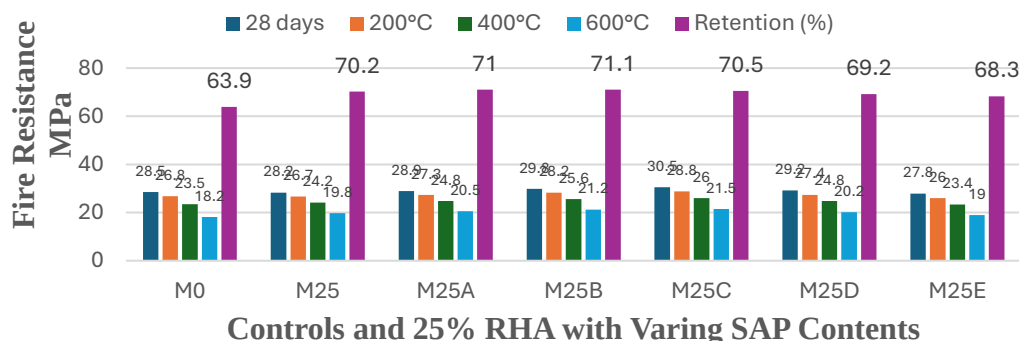


Figure 4: Compressive strength and residual-strength retention of concrete containing 25% RHA at different SAP dosages

Residual Compressive Strength and Strength Retention of RHA-SAP Concrete at 600 °C

Table 2 summarizes the comparative residual compressive-strength performance of the mixtures containing 0.3% SAP at different RHA

replacement levels following exposure to 600 °C. The results indicate that M15C exhibited the highest residual strength and percentage retention, demonstrating the most favourable elevated-temperature performance among the investigated compositions.

Table 2. Comparative residual compressive strength and strength retention of RHA-SAP concrete at 600 °C

Sample ID	RHA (%)	SAP (%)	Initial strength (MPa)	Residual strength at 600 °C (MPa)	Strength retention (%)
M0	0	0	28.5	18.2	63.9
M10C	10	0.3	32.5	24.6	75.7
M15C	15	0.3	34.2	27.8	81.3
M20C	20	0.3	32.6	24.3	74.5
M25C	25	0.3	30.5	21.5	70.5

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Note. M0 is the PLC control; M10C, M15C, M20C and M25C contain 0.3% SAP with the indicated RHA replacement levels. M15C achieved the highest residual strength and retention at 600 °C.

Engineering Implications and Limitations

The superior residual compressive strength of concrete containing 15% RHA and 0.3% SAP demonstrates its potential for applications requiring improved mechanical performance following elevated-temperature exposure. This finding may also provide useful information for post-fire structural assessment and rehabilitation. However, residual compressive strength alone does not establish structural fire resistance, as actual performance depends on member dimensions, reinforcement conditions, heating duration, applied loads and spalling behaviour. Furthermore, although higher RHA replacement levels offer greater cement substitution and potential environmental benefits, these advantages require further assessment through comprehensive mechanical, durability and environmental evaluations. Consequently, additional structural-scale fire testing and life-cycle assessment are recommended to establish the practical applicability and sustainability of RHA-SAP concrete.

CONCLUSIONS

Based on the experimental findings, the following conclusions were drawn:

1. The incorporation of RHA and SAP generally improved residual compressive-strength retention compared with conventional PLC concrete. The optimum mixture, M15C, achieved the highest residual strength of 27.8 MPa and 81.3% retention at 600°C, representing approximately 52.7% higher residual compressive strength than M0.
2. At 0.3% SAP, residual-strength retention at 600°C was 75.7%, 81.3%, 74.5% and 70.5% for 10%, 15%, 20% and 25% RHA, respectively. These findings indicate that increasing RHA replacement beyond 15% did not further improve elevated-temperature residual-strength performance.

3. SAP dosage influenced the observed residual-strength behaviour, with 0.3% generally providing the most favourable absolute residual compressive strength. However, within the 25% RHA series, M25B (0.2% SAP) achieved slightly higher percentage retention (71.1%) than M25C (0.3% SAP), which recorded the highest absolute residual strength of 21.5 MPa.

RECOMMENDATIONS

Based on the experimental findings, the following recommendations are proposed:

1. The mixture containing 15% RHA and 0.3% SAP (M15C) is recommended for further investigation as a promising sustainable concrete composition where improved residual compressive strength following elevated-temperature exposure is required.
2. Detailed microstructural and thermal analyses, including scanning electron microscopy (SEM), thermogravimetric analysis (TGA) and pore-structure characterization, are recommended to clarify the mechanisms responsible for strength retention and thermal deterioration.
3. Life-cycle assessment and embodied-carbon evaluation should be conducted to quantify the environmental benefits associated with partial PLC replacement using RHA, particularly at higher replacement levels

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