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Mechanical Strength and Durability of Rice Husk Ash–Corn Cob Ash Ternary Blended Concrete under Elevated Temperatures

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ABSTRACT
The utilisation of agricultural waste ashes as supplementary cementitious materials offers opportunities to reduce cement consumption and improve resource efficiency in concrete production. This study investigated the mechanical strength and durability characteristics of ternary blended concrete incorporating rice husk ash (RHA) and corn cob ash (CCA) as partial replacements for Portland limestone cement. Nine concrete mixtures comprising one control, four binary blends, and four ternary blends were initially investigated. Compressive, splitting tensile and flexural strengths were evaluated at curing ages of 7, 28, 56 and 90 days. The mixture containing 10% RHA and 5% CCA exhibited the highest reported later-age strength among the investigated ternary mixtures, attaining compressive, splitting tensile and flexural strengths of 41.50, 2.94 and 3.90 N/mm², respectively, at 90 days. This mixture was subsequently subjected to temperatures of 200, 400, 600 and 800 °C, followed by residual compressive strength and durability assessments. Residual compressive strength decreased with increasing temperature, reaching 7.50 N/mm² at 800 °C after 90 days of curing. Water absorption, acid resistance and abrasion performance were also evaluated. The findings indicate that a 15% combined replacement of cement with RHA and CCA can produce favourable mechanical strength under the investigated curing conditions. However, severe thermal exposure substantially reduced residual strength and durability performance. The findings support the selection of sustainable cementitious binders for construction applications where resistance to heating, post-exposure durability, structural safety, and long-term reliability are important considerations. The results further emphasis the importance of balancing cement replacement levels with curing duration and anticipated service conditions when designing more resilient concrete mixtures.

Keywords: Rice Husk Ash, Corn Cob Ash, Ternary Concrete, Elevated Temperature, Durability

INTRODUCTION

Concrete remains essential to modern infrastructure, but the environmental cost of cement production has encouraged renewed interest in agricultural residues as supplementary cementitious materials. Rice husk ash (RHA) and corn cob ash (CCA) are particularly relevant in farming regions where these residues are readily available. Their value depends not only on diverting waste from disposal but also on whether they can maintain dependable concrete performance. Material characterisation showed that both rice husk ash (RHA) and corn cob ash (CCA) can be used as pozzolans, with combined oxide contents of 79.55% and 63.45%, respectively. XRD scans confirmed that both ashes are full of amorphous silica. Since this non-crystalline structure drives reactivity, RHA's more disordered structure confers higher pozzolanic activity. (Barbhuiya et al., 2025; Montazeri et al., 2025; Williams et al., 2026).

A binary blend uses one supplementary cementitious material, whereas a ternary blend combines two. The potential advantage is complementary particle packing and pozzolanic action, although the actual outcome depends on ash chemistry, fineness, dosage, and curing. Recent studies have increasingly emphasised the importance of optimising the proportions of supplementary cementitious materials in multi-ash concrete mixtures rather than assuming that increasing cement replacement levels will consistently improve mechanical performance.
(Jing et al., 2025; Nadgouda et al., 2025; Gora et al., 2026). Previous studies on RHA–CCA concrete concerning the combined effects of curing age and elevated-temperature exposure are limited; therefore, this study aimed to evaluate the mechanical strength development of concrete incorporating rice husk ash and corn cob ash as partial cement replacements and to investigate the residual strength and durability characteristics of the selected ternary mixture following exposure to elevated temperatures.

The study examines the ternary component of an experimental programme conducted at Ahmadu Bello University, Zaria. It considers mixture selection, strength development and the subsequent performance of the selected blend after exposure to temperatures between 200 and 800 °C. Particular attention is given to the relationship between residual strength and durability indicators. The thermal performance of RHA-containing concrete is a growing area of investigation, although results from other binder systems cannot be directly transferred to the RHA–CCA mixture studied here (Ankit et al., 2026).

MATERIALS AND METHODS

Materials

Portland limestone cement (CEM II/B-L 42.5N) was obtained in Samaru, Zaria-Nigeria. River sand and crushed-stone coarse aggregate were sourced locally. Mixing and curing water came from the Ahmadu Bello University water works. Rice husks were obtained from a rice mill in Zaria; corn cobs came from farmland in the Palladan area of Zaria. Both residues were subjected to control burning at the university's Chemical Engineering laboratory. The physical properties of the cement and aggregates met the relevant standard requirements. The cement recorded a consistency of 31%, with initial and final setting times of 2 hrs 5 mins and 3 hrs 39 mins, respectively. Aggregate tests, including specific gravity and ash calcination, ball milling, and oxide composition, also confirmed their suitability for concrete production (Williams et al., 2026).

Mixture Design and Selection

All mixtures used a nominal cement: fine aggregate: coarse aggregate ratio of 1:2.22:3.27 and a reported water–cement ratio of 0.57, calculated using the original cement mass. Nine mixes were produced: one control, four binary mixtures and four ternary mixtures. The binary mixtures helped establish separate ash responses; the four ternary mixtures formed the central comparison for this paper. Replacement percentages refer to cement substituted by ash.

Table 1: Control and Ternary Mixture Cement Replacement

Mix	RHA (%)	CCA (%)	Total (%)
Control	0	0	0
T1	15	5	20
T2	15	10	25
T3	10	5	15
T4	10	10	20

The 10% RHA + 5% CCA blend (T3) was identified as the optimum ternary mixture on the basis of the mechanical strength results. Subsequent elevated-temperature and durability testing focused on this selected blend. Therefore, thermal resistance cannot be ranked across all four ternary mixtures using the available evidence.

Methods

This study applied the following research methods to achieve its goals. Compressive strength was measured on 100 × 100 × 100 mm cubes in accordance with BS EN 12390-3:2019. Splitting tensile strength used 100 × 200 mm cylinders (BS EN 12390-6:2023), while flexural strength followed BS EN 12390-5:2019. Three test samples were used. The primary strength series covered 7, 28, 56, and 90 days of curing.

Sample Strength Test Setup

Equation 1 was used to calculate the sample's compressive strength, and Plate I shows the compressive strength test setup with a loading rate of 4 kN/min.

$$\text{Compressive strength} = \frac{P}{A} \quad (1)$$

P = load at failure, A = sample cross-sectional area

Plate II presents the test setup for the splitting tensile strength, while the strength was calculated using equation 2. The flexural strength is calculated using equation 3, while Plate III shows the test setup.



Plate I: Compressive strength test



Plate II: Splitting tensile strength test



Plate III: Flexural strength test



Plate IV: Samples soaked in water



Plate V: Towel-drying of sample



Plate VI: H_2SO_4 attacked samples



Plate VII: Sample washing

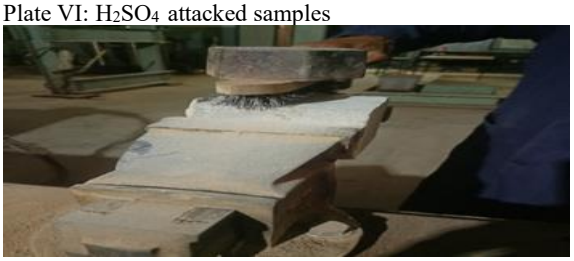


Plate VIII: Concrete abrasion test

Thermal Exposure and Durability Methods

After initial curing, the specimens of the optimum ternary mix were exposed to 200, 400, 600 and 800 °C, alongside unheated reference specimens. The specimens were heated at each of the mentioned temperatures in a High-Temperature Laboratory Electric Muffle Furnace (Model: SP-1700B) for two hours from the target temperature at a heating rate of 15°C/min to enable heat to reach the central core of the specimens.

The residual compressive strength was evaluated after heating. Water absorption followed the BS 1881-122 procedure and the test setup as presented in Plates IV and V. The sulfuric acid attack was assessed through mass loss and residual compressive strength using ASTM C267/C267M as shown in Plates VI and VII. The abrasion resistance followed ASTM C779/C779M, and Plate VIII presents the test setup. The samples were allowed to cool naturally in air for 24 hours to ambient temperature and then tested.

Interpretation and Comparison

Temperature and curing age were treated as the principal explanatory variables. For strength retention, the relevant expression is residual strength divided by corresponding unheated strength, multiplied by 100. For acid attack and abrasion, increasing percentage mass loss indicates worsening resistance; for absorption, increasing water uptake suggests greater accessible porosity or connected transport pathways.

RESULTS AND DISCUSSION

The results of the laboratory tests are presented and discussed in relation to standard codes and engineering practices.

Mechanical Strength Development

The five-mixture screening series showed a clear influence of curing age and binder composition. Figures 1, 2, and 3 present the compressive, splitting tensile, and flexural strength test results for the control and ternary mixes, respectively, to assess their mechanical properties and suitability for use.

Compressive Strength of Control (CM) and Ternary (TM) Concretes

Figure 1 presents the compressive strength results for the control and ternary-blended concrete mixes.

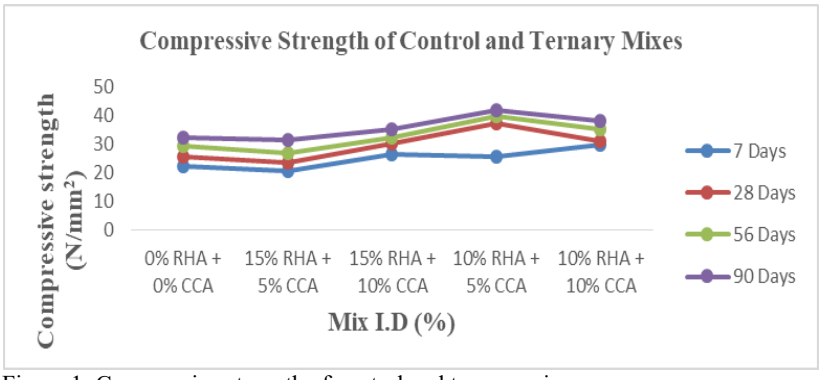


Figure 1: Compressive strength of control and ternary mixes

The results demonstrate that curing age strongly influenced the effectiveness of RHA and CCA, with strength steadily improving as curing progressed. The ternary results demonstrate that the performance of the concrete depended on the balance between RHA and CCA rather than simply increasing the total ash content. The 10% RHA + 5% CCA mixture consistently developed the strongest later-age performance, rising from 25.5 N/mm² at 7 days to 41.5 N/mm² at 90 days. The result therefore suggests that the two agricultural ashes can act complementarily when appropriately proportioned, with RHA contributing substantially to later-age pozzolanic development and CCA providing a complementary contribution to early and later strength.

The ternary blend of rice husk ash and corn cob ash outperforms the control mix due to a dense micro-filler effect

driving early strength, a pozzolanic reaction between active silica and the remaining calcium hydroxide, resulting in secondary C-S-H gel production, and continuous long-term maturation as unreacted ash and moisture sustain strength gains past 90 days. Differences in ash production temperature, fineness, amorphous silica content, chemical composition, cement type, water–binder ratio, and curing conditions can change the optimum replacement level (Barbhuiya et al., 2025; Li, 2025). The mechanical strength results show that incorporating rice husk ash and corn cob ash can produce concrete with competitive and superior later-age performance compared with the conventional control mixture. Biswas et al., (2026) found that replacing 10–15% of the cement with rice husk ash boosted compressive strength by roughly 11.4%. Beyond that strength gain, RHA blending also refines the concrete's pore structure, making it less porous and more resistant to chloride penetration. This suggests a possible synergistic effect between the two ashes, where their complementary pozzolanic, filler, and particle-packing effects produced a denser and stronger cementitious matrix. This result aligned with the findings of Ullah et al., (2026)

Split Tensile Strength of Control (CM) and Ternary (TM) Concretes

Figure 2 presents the results of the splitting tensile strength of control and ternary concretes.

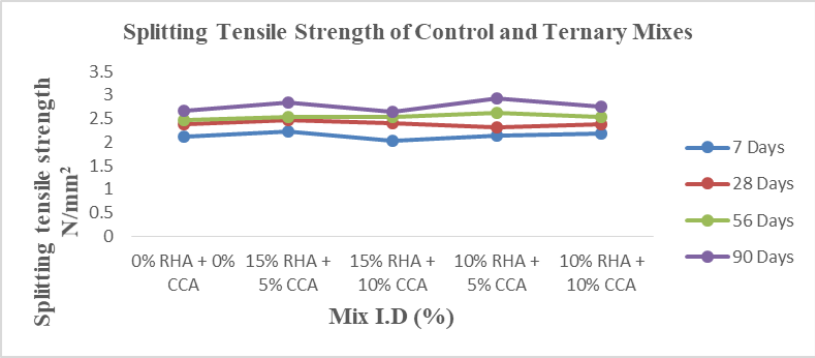


Figure 2: Split tensile strength test results of control and ternary mixes

Tensile strength depends on the physical bonding and crack-bridging ability of the matrix. The resulting refinement of the paste and improvement in the paste–aggregate interface as curing continued helped the concrete resist tensile cracking more effectively. With RHA and CCA partially replacing cement, continued pozzolanic reactions and C–S–H formation gradually densification of the interfacial transition zone (ITZ) between the aggregate and the cement paste, often leading to greater tensile-strength gains at later ages (Barbhuiya et al., 2025; Cherkos, 2025; Terlumun et al., 2025). By day 56 and extending out to day 90, the ternary mix clearly pulls ahead, finishing at a strength of 2.94 N/mm² compared to the control's 2.66 N/mm². The control mix shows steady improvement in tensile strength, increasing from 2.11 N/mm² at 7 days to 2.66 N/mm² at 90 days. It was observed that increasing the total ash content did not automatically produce higher tensile strength. For example, the 10% RHA + 10% CCA mixture reached 2.76 N/mm² at 90 days, which was lower than the 2.94 N/mm² obtained with 10% RHA + 5% CCA. Similarly, the 15% RHA + 10% CCA mixture reached 2.64 N/mm². This indicates that there was a suitable balance between cement replacement and the amount of reactive ash available to contribute to the developing matrix. Excessive replacement may reduce the amount of Portland cement available for primary hydration and may also increase water demand or porosity.

Flexural Strength Test Results of Control (CM) and Ternary (TM) Concretes

Figure 3 shows the flexural strength of the control, binary, and ternary concrete mixes.

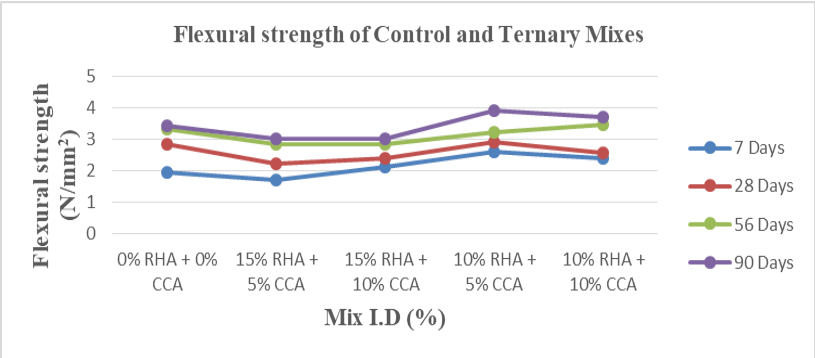


Figure 3: Flexural strength test results of control and ternary mixes

In the flexural strength measurement, the control mix showed steady improvement, rising from 1.95 N/mm² at 7 days to 3.43 N/mm² at 90 days. The ternary blend, 10% RHA + 5% CCA, performed optimally by increasing from 2.60 to 3.90 N/mm², resulting in a 50% increase in strength between 7 and 90 days of curing. This strength increase reveals that curing time maximizes the potential of agro-waste ashes. Rochmah et al., (2026), found that this could be attributed to the combined ashes that improved the cement matrix through pozzolanic activity and better particle packing, leading to

enhanced densification of the concrete. Barbhuiya et al., (2025) in their studies affirmed that suitable RHA/CCA combinations can improve concrete strength, although the optimum proportion depends on the mix and property being measured. The results show that the 10% RHA + 5% CCA mixture was the best-performing at 90 days, yielding the highest compressive, split tensile, and flexural strengths. This suggests that getting the right balance between RHA and CCA is more important than simply increasing the total ash content. The 10% RHA + 5% CCA mixture performed well in all three strength tests: compressive, tensile, and flexural. This is supported by the findings of Anderson & Adesina (2026), who inferred that ternary and quaternary SCM systems have been shown to outperform binary blends under optimized conditions. This suggests that combining RHA and CCA can give a good balance between early strength development and continued strength gain at later ages. Ullah et al., (2026) demonstrated that agricultural-ash concrete performs best within a defined optimum replacement range, influenced by ash quality, fineness, reactivity and dosage. They inferred that beyond this range, strength can decline due to cement dilution, particle agglomeration, and poorer hydration.

The ternary mixture exceeded the 90-day control in all three mechanical measures. The compressive advantage was approximately 29.6%, while splitting tensile and flexural strengths were about 10.5% and 13.7% higher, respectively. These differences suggest that the selected blend may strengthen both the paste and the paste–aggregate interface.

The findings identify an optimum within the particular materials and replacement levels tested, not a universal formulation. Ash fineness, burning conditions, reactive silica content, cement composition, and curing practice can all alter the balance between dilution and secondary hydration (Barbhuiya et al., 2025; Montazeri et al., 2025; Williams et al., 2026).

Presentation of Durability Test Results

Results of water absorption, chemical attack, and abrasion resistance tests on the ternary mix (TM), (10% RHA + 5% CCA), are presented in Figures 4-6

Residual Compressive Strength of the TM Concrete

Figure 4 presents the results of the residual compressive strength of the ternary blended concrete.

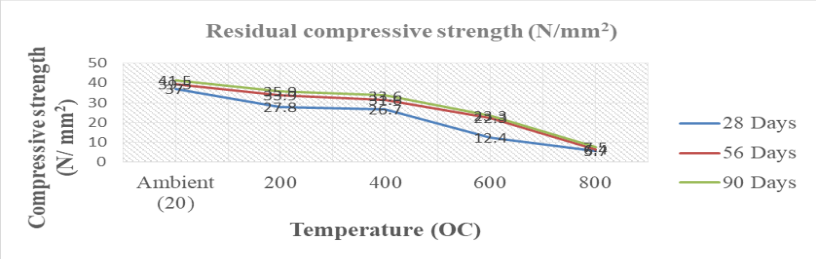


Figure 4: Residual compressive strength of the TM concrete

At 200 °C, the concrete shows mild drying and slight darkening due to moisture loss, then turns pinkish-red at 400 °C as iron compounds oxidize and calcium hydroxide begins to dehydrate, fades to a dull grey at 600 °C as portlandite fully decomposes and micro-cracking increases, and finally becomes pale whitish-grey at 800 °C, indicating severe thermal damage and breakdown of the internal structure.

Figure 4 presents the TM concrete at its best in terms of strength at ambient temperature, having 37.0, 39.5, and 41.5 N/mm² at 28, 56, and 90 days, respectively. This confirms that continued curing improved the concrete before thermal exposure. When exposed to 200 °C, the concrete decreased in strength from 41.5 N/mm² to 39.5 N/mm² for the 90-day curing. This mild drop could be due to evaporating water and internal thermal stress rather than any breakdown of the cement matrix. However, at 800 °C, the concrete had lost about 81.9% of its strength at 90 days of curing, with residual values dropping to about 5.7–7.5 N/mm². This sharp drop in strength could be attributed to severe dehydration, widespread micro-cracking, thermal incompatibility, and damage to the concrete matrix. In relation to their strength at room temperature, the specimens retained only about 15% of their 28-day strength, 16% of their 56-day strength, and 18% of their 90-day strength. At this temperature, severe dehydration, widespread micro-cracking, thermal incompatibility, and damage to the cement paste had significantly weakened the concrete (Balagopal et al., 2020; Nazari et al., 2024).

The figure shows that the 56-day and 90-day cured specimens generally performed better than the 28-day specimens up to 600 °C. This could be due to the longer curing period, which gave more time for hydration and pozzolanic reactions to take place before heating. As a result, the matrix becomes denser and stronger, which produces a more robust structure that could withstand thermal damage more effectively.

The results indicate that temperature had a far greater negative effect on compressive strength than curing age had a positive one. The concrete still performed fairly well at 200 and 400 °C, but its strength dropped sharply at 600 °C and fell even more at 800 °C. Longer curing periods, especially 56 and 90 days, generally helped improve residual strength because they allowed the concrete to develop a more mature and well-bonded matrix. The use of RHA and CCA is therefore mainly beneficial because these materials supposedly improve the concrete's early microstructure and strength through pozzolanic reactions and the pore-filler effect as indicated in the result. This helps the concrete resist moderate levels of heat, but at very high temperatures, particularly around 800 °C, dehydration, cracking, and the breakdown of the cementitious matrix become too severe for the pozzolanic benefits to offset.

Water Absorption of the TM Concrete

Figure 4.5 presents the water absorption of the ternary blended concrete at ambient and elevated temperatures of 200 ^{O}C, 400 ^{O}C, 600 ^{O}C, and 800 ^{O}C for curing periods of 28, 56, and 90 days.

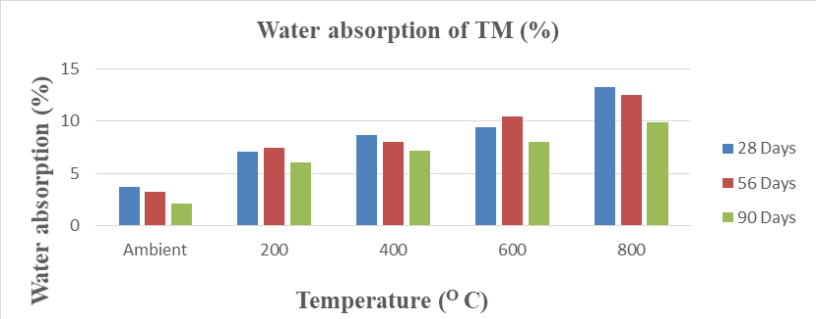


Figure 5: Water absorption of TM at ambient and elevated temperatures (%)

At 28 days, water absorption increased from 7.07% at 200^{O}C to 13.25% after heating at 800^{O}C. A similar trend was observed at 56 days, with absorption increasing from 7.42% at 200^{O}C to 12.52% at 800^{O}C. The 90-day concrete recorded the lowest absorption overall, ranging from 6.09% at 200^{O}C to 9.92% at 800^{O}C. These results show that both temperature and curing age influenced the ability of the concrete to absorb water. The water-absorption results show a clear increase in moisture uptake as the exposure temperature rose. The higher absorption observed at elevated temperatures can be linked to the physical and chemical changes that occur within the cementitious matrix during heating. As temperature increases, free and physically bound water is progressively removed, while further heating causes dehydration of cement hydration products. At higher temperatures, these changes can be accompanied by thermal incompatibility between the cement paste and the aggregates, leading to microcracking and an increase in pore volume. Consequently, the heated concrete develops more pathways for water to enter during subsequent absorption testing. Recent research on RHA-containing concrete similarly reports that elevated temperatures can cause significant physicochemical deterioration, while thermal exposure alters the pore structure and moisture condition of the cementitious matrix (Ankit et al., 2026; Nazari & Toufigh, 2024)). Though the extended curing could not completely prevent thermal damage, it appears to have improved the concrete's ability to withstand the subsequent increase in porosity and moisture ingress caused by elevated temperature exposure.

Sulfuric Acid Attack on the TM

The results of the chemical attack using sulfuric acid on the control and optimal ternary blended concrete at 28, 56, and 90 days curing for the 200^{O}C, 400^{O}C, 600^{O}C and 800^{O}C temperature exposure is presented in Figure 6

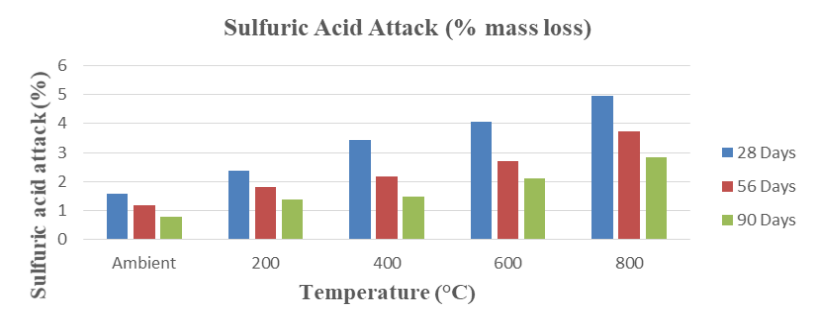


Figure 6(a): Sulfuric acid attack on the TM (% mass loss)

The results in Figure 6(a) demonstrate that curing age had a beneficial effect on acid resistance, whereas elevated temperature had a detrimental effect. The 90-day concrete retained more mass after acid exposure than the younger specimens, indicating the benefit of a more mature matrix. Nevertheless, exposure to 600–800^{O}C caused substantial deterioration, resulting in higher mass loss and markedly lower acid-exposed compressive strength. This confirms that the beneficial effect of the RHA–CCA ternary system cannot completely offset the severe physical and chemical damage produced by high-temperature exposure. Wu et al., (2026) had a similar trend in their studies on the Performance Degradation mechanism of UHPC under combined thermal and sulfate exposure.

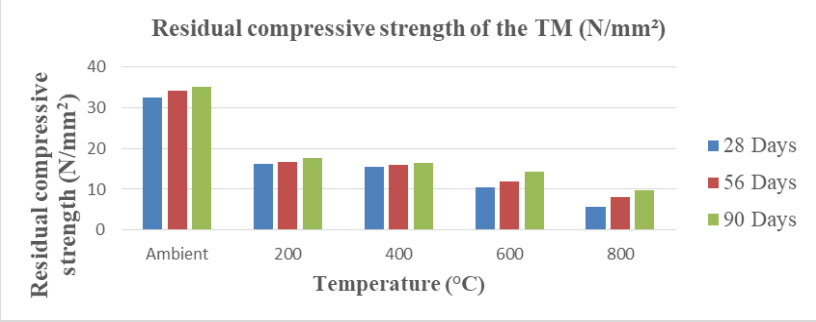


Figure 6(b): Sulfuric acid attack on the TM (Residual compressive strength)

Figure 6(b) shows a modest increase in compressive strength with curing age, but the strength gradually decreases as the exposure temperature increases. This indicates that the combined action of heat and acid is more damaging than when either factor acts alone. Heat first disrupts and loosens the concrete's internal structure, creating cracks and pathways within the matrix, and the acid then penetrates these weakened zones more easily, speeding up chemical attack and further weakening the material. This helps explain why the residual compressive strength of the concrete continues to drop as the exposure temperature rises. Similar findings were reported by Zhang et al., (2025), who showed that the interaction between temperature and sulfate leads to progressive internal damage in concrete. Hu et al., (2025) also noted that elevated temperature can intensify the deterioration of concrete exposed to sulfate-rich environments.

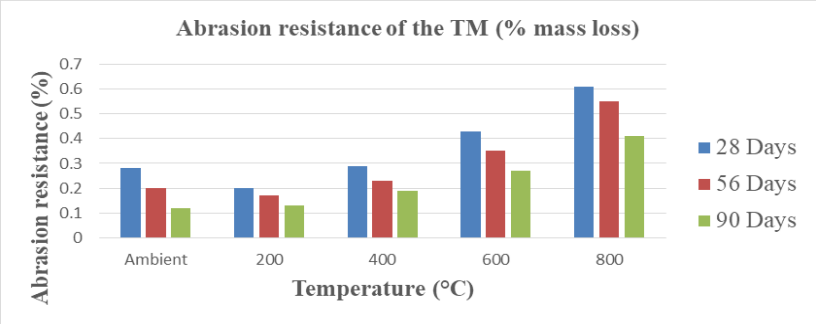


Figure 7: Abrasion resistance of the TM (% mass loss)

The abrasion results show that the concrete's resistance to surface wear declined as the exposure temperature increased. Brushing load of 2kg was used at 50 cycles per test phase amounting to 600 strokes per cube. At 28 days, mass loss rose from 0.20% at 200 °C to 0.61% at 800 °C, while at 56 days it increased from 0.16% to 0.55%. By 90 days, the effect was much more severe as mass loss climbed from 0.13% at 200 °C and 0.19% at 400 °C to 0.27% at 600 °C and 0.41% at 800 °C, showing that severe heating substantially weakened the surface and made it easier to remove material by abrasion. This trend agrees with recent research showing that exposure to elevated temperatures progressively damages the internal structure of concrete. As temperature rises, dehydration of cementitious products, thermal stresses, pore enlargement, and microcrack development become more pronounced. These changes weaken the surface and make the concrete more susceptible to material loss during abrasion, thereby reducing its overall abrasion resistance (Su et al., 2025; Zhang et al., 2025; Abdelmelek et al., 2026). In their research, Su et al., (2025) reported a substantial increase in concrete porosity as temperature increased from 200 to 500 °C, while Zhang et al., (2025) identified microcracking, pore development, and deterioration of the cement matrix as major mechanisms of thermal damage. Abdelmelek et al., (2026) likewise observed progressive microstructural deterioration and loss of mechanical performance after elevated-temperature exposure.

Conclusion

The study investigated the mechanical strength development and durability characteristics of ternary blended concrete incorporating rice husk ash and corn cob ash as partial replacements for Portland limestone cement. Among the investigated ternary mixtures, the combination of 10% rice husk ash and 5% corn cob ash exhibited favourable later-age mechanical performance, attaining compressive, splitting tensile and flexural strengths of 41.50, 2.94 and 3.90 N/mm², respectively, after 90 days of curing. However, elevated-temperature exposure substantially reduced the residual compressive strength of the selected mixture, particularly at 600 and 800 °C. The durability assessments also indicated deterioration in material performance under increasingly severe thermal conditions. These findings suggest that the selected ternary blend may provide a useful alternative cementitious formulation under the investigated curing conditions.

Portland limestone cement can be partially replaced with RHA and CCA at a total replacement level of 15% for optimum performance, in the proportion of 10% RHA and 5% CCA. Exposure to 400°C could be considered safe for the 28-day cured specimens, while 600°C could be considered safe for the 90-day cured specimens.

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