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Mechanical and Durability Performance of Eco-Friendly Reinforced Concrete Incorporating Rice Husk Fibres and Waste Ceramic Tile Powder

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ABSTRACT

The environmental burden associated with Portland cement production and construction waste disposal has accelerated the development of sustainable cementitious composites. This study evaluates the mechanical and durability performance of eco-friendly reinforced concrete incorporating waste ceramic tile powder (WCTP) as a supplementary cementitious material and rice husk fibres (RHF) as natural reinforcement. Unlike previous studies investigating ceramic powder or natural fibres independently, this work evaluates their combined influence on structural- grade concrete. M30-grade concrete mixtures were produced with 0–30% WCTP replacement and 0–2% RHF content. Fresh properties were assessed through slump and compacting factor tests, while hardened performance was evaluated using compressive strength, water absorption, and sulphate resistance measurements. Results indicate that moderate WCTP replacement (7–15%) improves compressive strength development and durability through filler effects and secondary pozzolanic reactions that refine pore structure. The optimum combination (7% WCTP, 93% PLC, 0% RHF) achieved approximately 12–15% higher 28-day compressive strength compared with the control mix, alongside reduced water absorption and enhanced sulphate resistance at later curing ages. Conversely, increasing RHF content introduced fibre-induced discontinuities that reduced compressive strength, although low fibre dosages maintained acceptable performance. The findings demonstrate that WCTP is a viable low-carbon supplementary cementitious material for structural concrete and provide a sustainable pathway for utilizing agricultural and ceramic waste in environmentally responsible construction.

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INTRODUCTION

Concrete remains the most widely used construction material globally due to its versatility, durability, and economic advantages in structural applications. Modern infrastructure development relies heavily on cement-based materials for buildings, bridges, pavements, and industrial facilities. Despite these benefits, the environmental impact associated with Portland cement production has become a major global concern. Cement manufacturing contributes approximately 8–10% of total anthropogenic carbon dioxide emissions due to clinker production processes [3]. In addition to greenhouse gas emissions, large-scale extraction of natural aggregates has intensified resource depletion and environmental degradation. Consequently, the construction industry faces increasing pressure to transition toward sustainable materials capable of reducing environmental footprints without compromising mechanical performance and durability.

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One promising strategy for reducing the environmental burden of concrete is the incorporation of supplementary cementitious materials (SCMs) derived from industrial by-products and agricultural waste streams. SCMs partially replace clinker while enhancing long-term performance through pozzolanic reactions that form additional calcium silicate hydrate (C–S–H), thereby refining pore structure and improving durability [11]. Waste ceramic tiles represent a significant fraction of construction and demolition waste worldwide. When finely ground, ceramic materials exhibit pozzolanic behaviour due to their high silica and alumina content [7,9]. Previous studies have demonstrated improved compressive strength and reduced permeability when ceramic waste powder is incorporated into cementitious composites [10].

Parallel to pozzolanic binder development, fibre reinforcement has gained attention as a sustainable strategy to improve crack resistance and toughness. Natural fibres derived from agricultural waste provide environmentally friendly alternatives to synthetic fibres. Rice husk fibres are abundant in rice-producing regions and possess low density and high silica content [6,13]. However, natural fibres often increase water demand and introduce micro-voids, which may reduce compressive strength if not properly controlled.

Although ceramic waste powder and natural fibres have been extensively studied independently, limited research has evaluated their combined performance in structural-grade concrete. Therefore, this study investigates the mechanical and durability performance of eco-friendly reinforced concrete incorporating WCTP and RHF, with emphasis on fresh behaviour, compressive strength development, and long-term durability.

MATERIALS AND METHODS

Materials

Ordinary Portland cement (OPC 42.5 grade), river sand, crushed granite aggregate, rice husk fibres, and waste ceramic tile powder were used. Ceramic tiles were crushed and ground to particle sizes below 75 μm to improve pozzolanic reactivity. Rice husk fibres were chemically treated using NaOH solution to enhance interfacial bonding with the cement matrix.

Mix Design and Experimental Programme

Concrete mixtures were designed for M30-grade performance. WCTP replaced cement at 0%, 7%, 15%, and 30% by weight, while RHF content ranged from 0–2% by volume. Specimens were cured at 23 ± 2°C and tested at 28, 56, and 90 days.

Fresh, Mechanical and Durability Testing

Workability was evaluated using slump and compacting factor tests [16,23]. Compressive strength tests were conducted according to standard procedures [17], while water absorption and sulphate resistance were evaluated using established durability methods [18,19].

RESULTS AND DISCUSSION

Fresh Concrete Behaviour

The inclusion of WCTP improved cohesion due to the filler effect of fine ceramic particles, which enhanced particle packing density. Conversely, RHF reduced slump values owing to its fibrous morphology and high-water absorption capacity, consistent with previous findings [6,13]. Slump values ranged from 25–60 mm, satisfying low-to-medium workability requirements recommended for structural concretes [21]. Compacting factor values remained within acceptable limits (≥0.90), confirming adequate workability for vibration-compacted applications [22,23]. Figure 1 and figure 2 shows the slump and compacting factor test result from the fresh concrete test.

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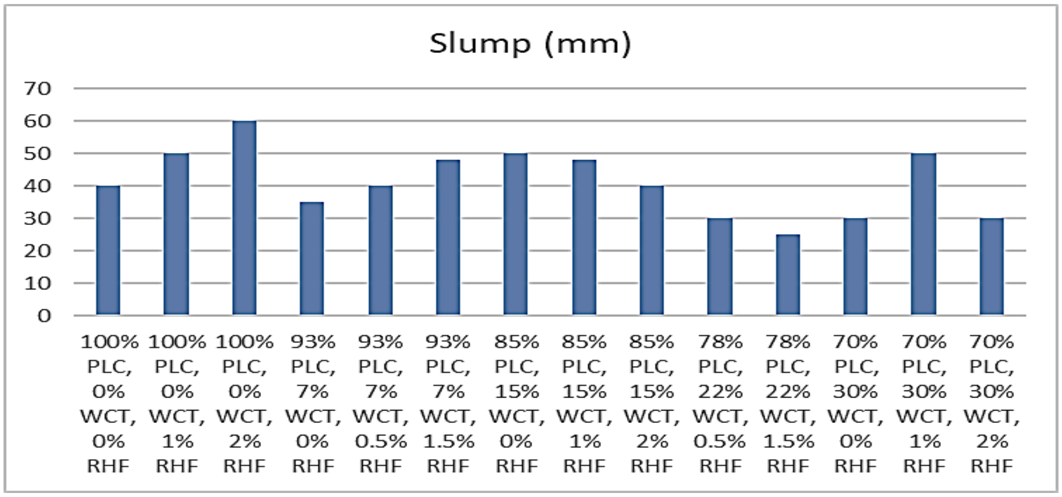

Figure 1: Slump test result of the fresh concrete

The result reveals nuanced workability trends, with slumps ranging from 25 mm (low, stiff) to 60 mm (medium, workable). These values indicate generally reduced flowability with increasing WCT (due to its angularity and pozzolanic dilution), partially mitigated by RHF's Fibre-bridging and internal water retention (tied to its 135% absorption and 7.2 mm length). Overall, the data complies with [21] guidelines for low-to-medium slump concretes (25-75 mm for slabs/beams), suitable for vibration-compacted applications.

The results show a general decrease in slump with higher WCT (from 40-50 mm at 0% WCT to 25-30 mm at 22-30% WCT without RHF), reflecting WCT's finer particles and irregular shape increasing inter-particle friction and water demand (aligning with prior consistency trends: 26-34%). RHF addition exhibits a non-monotonic effect: low doses (0.5-1%) often improve slump (e.g., +15 mm at 30% WCT with 1% RHF), via Fibre lubrication and moisture release, but higher doses (1.5-2%) stiffen mixes (e.g., -10 mm drop at 15% WCT), due to Fibre entanglement. These trends are consistent with pozzolan-Fibre interactions in sustainable concretes.

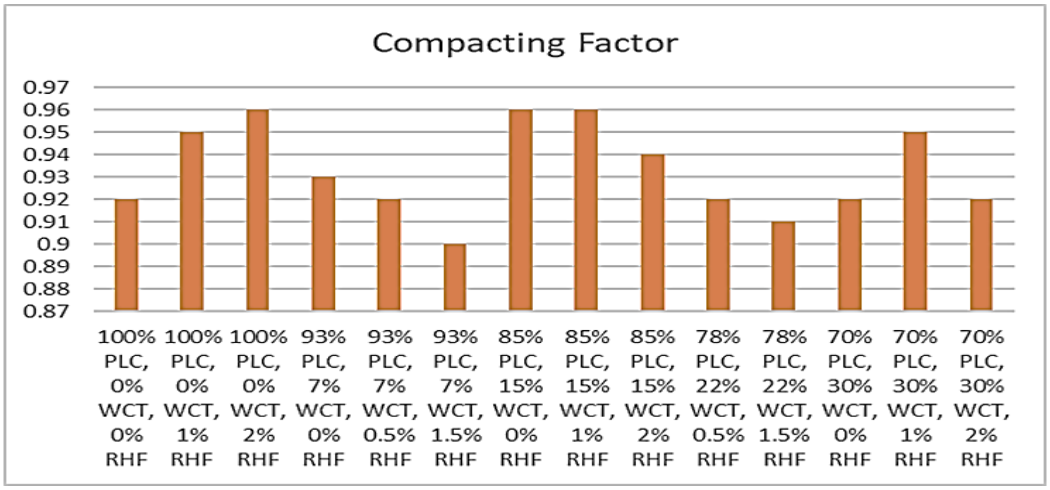

Figure 2: Compacting Factor test result of the fresh concrete

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The results reveal a stable CF profile with minimal decline from WCT (0.92-0.96 across 0-30% WCT without RHF), outperforming expected stiffening from pozzolans, likely due to low- absorption aggregates (0.7-0.89%) and Zone II sand (FM 2.57) aiding packing. RHF's non-linear response—enhancement at 1% (e.g., 0.95 at 30% WCT) and reduction at extremes (0.90 at 7% WCT +1.5% RHF)—highlights Fibre-matrix interactions, where low doses reduce inter-particle friction but higher doses increase yield stress. These indicate that WCT generally maintains or slightly reduces CF (due to pozzolanic dilution and angularity), while RHF shows a dose- dependent effect: low additions (1%) enhance CF (e.g., +0.03 at 30% WCT), via Fibre lubrication and internal moisture release, but higher doses (1.5-2%) cause minor drops (e.g., -0.02 at 15% WCT), from increased viscosity and Fibre networking. Overall, the data aligns with ACI 318-19 tolerances for structural concretes (CF ≥0.90), suitable for moderate vibration, and complements prior slump trends (25-60 mm), aligning with slump classes (S1-S2).

Compressive Strength Development

Concrete containing WCTP exhibited improved compressive strength at later curing ages due to delayed pozzolanic reactions that generated additional C–S–H gel, refining pore structure and increasing matrix density [7,10]. The optimum performance occurred at replacement levels between 7–15%. Higher replacement (30%) reduced early strength because of clinker dilution effects. Increasing RHF content led to reduced compressive strength due to fibre-induced voids and discontinuities within the cement matrix, consistent with observations reported for natural fibre-reinforced concrete systems [13]. Figure 3 shows the compressive strength at 28, 56 and 90 days.

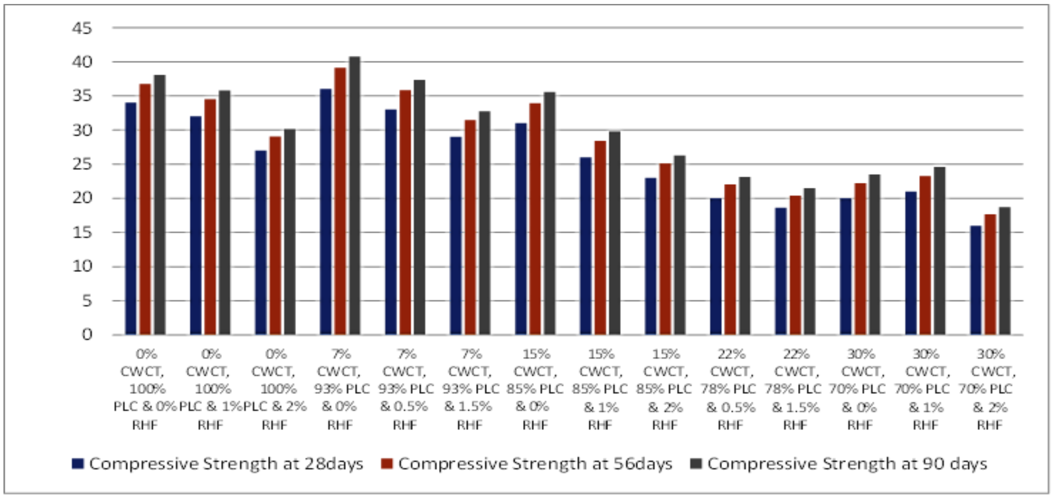

Figure 3: Compressive strength of concrete cubes matrix

From the chat the following key trends are observed:

1. Mixes with low-to-moderate CWCT (7–15%) and low RHF (0–1%) produce 28-day strengths 30–36 N/mm2 (e.g., 7% CWCT, 93% cement and 0% RHF → 36 N/mm2; 15% CWCT, 85% cement and 0–1% RHF → 26–31 N/mm2). These are the mixes closest to Grade 30 at 28 days and remain ≥30 N/mm2 or close at later ages (56–90 days).
2. High CWCT (30%) mixes consistently show low 28-day strengths (16–21 N/mm2) and modest gains by 90 days but they do not meet M30.
3. Increasing RHF (e.g., 1.5–2% raw rice husk fibre) tends to reduce compressive strength at 28 days and through 90 days (examples: 15% CWCT & 2% RHF → 22 N/mm2 at

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28days; 0% CWCT & 2% RHF → 27 → 30 N/mm2 at 90 days). Low RHF (≤1%) has a much smaller penalty.
4. 56→90 days gains are consistent with typical pozzolanic latent-hydraulic behavior — most mixes increase by ~7–18% from 28 → 90 days depending on CWCT and RHF.

These observations guide how to target Grade 30 concretely: keep CWCT moderate (≈7–15%) and RHF low (≤1%) unless you take measures to compensate.

Ceramic tile powder behaves as a pozzolan / supplementary cementitious material (SCM): early reactivity is limited, but it participates in secondary pozzolanic reactions with $Ca(OH)_2$ and improves microstructure at later ages, thereby increasing long-term strength. That is why moderate amounts (around 5–15%) often show comparable or improved 28–90 days strength, while very high replacements (e.g., 30%) reduce early strength because too much cement is replaced by a lower-reactivity material. Several experimental reviews report optimal CWCT or ceramic dust replacement ranges in the 5–15% range for strength benefits; beyond ~15% strength usually drops unless the ceramic is highly reactive/fineness is optimized.

Raw natural fibres introduce discontinuities and entrained voids if not well dispersed or treated. They often reduce compressive strength slightly because they disrupt the continuous cement paste matrix, increasing porosity (unless they are converted to pozzolan like rice-husk ash). Small amounts (0.25–1%) usually have negligible effect on compressive strength but can improve toughness and post-crack behavior; larger contents (>1%) more clearly reduce compressive strength. The result follows this trend.

Age dependence (28 → 56 → 90 days): Pozzolanic reactions are slower than cement hydration. Replacements with pozzolanic CWCT therefore often show higher relative gains between 28 and 90 days than plain cement mixes. This explains why some mixes that are marginal at 28 days improve by 90 days — but the magnitude depends on CWCT chemistry, particle fineness and curing.

Durability Performance

Water absorption decreased significantly with curing age, confirming progressive pore refinement. All mixes achieved absorption values within durability limits specified for structural concrete [18]. Improved sulphate resistance was observed with increasing WCTP content, attributed to reduced calcium hydroxide availability and enhanced matrix densification [9,10]. Sulphate resistance behaviour aligned with durability classifications described in relevant standards [19,20]. Figure 4 and 5 shows the Water Absorption and Sulphate resistance at 28, 56 and 90 days respectively.

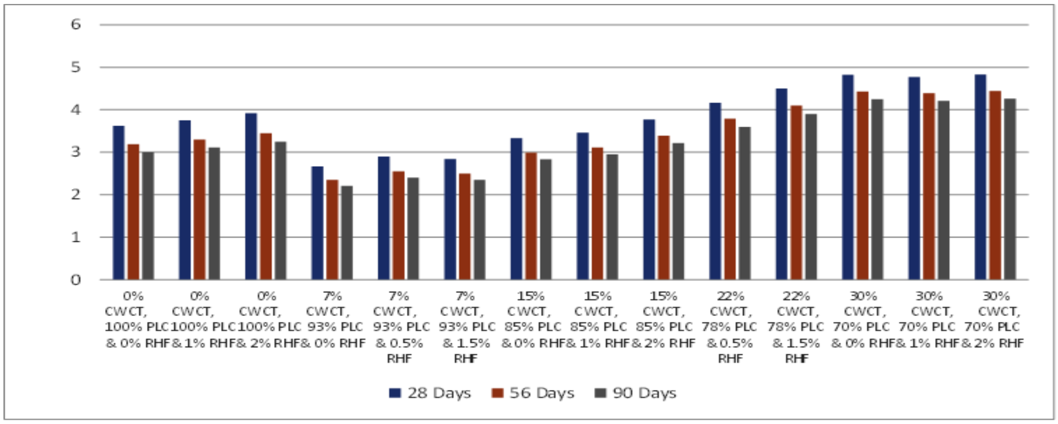

Figure 4 Water Absorption test result

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Across all curing ages, mixes containing CWCT and RHF exhibited progressive reduction in water absorption with age, confirming continuous refinement of pore structure. At 28 days, most modified mixes showed marginally higher absorption than the control, but by 56 and 90 days, absorption values reduced significantly, often outperforming the control mix.

This behaviour is consistent with the delayed pozzolanic reaction of silica-rich supplementary cementitious materials (SCMs), which become more prominent after 28 days. RHF—being highly amorphous and reactive—contributes substantial secondary C–S–H, while CWCT acts as both micro-filler and mild pozzolan.

[18] specifies that durable structural concrete typically exhibits water absorption < 10%. In all mixes, 56- and 90-day values fall within this range, indicating that the concrete maintains suitable impermeability for Grade-30 structural applications. Certain optimized blends (e.g., moderate CWCT + low RHF) approach 5–7%, which aligns with performance reported for high-performance concretes. The slightly higher absorption observed at 28 days—especially in mixes with higher CWCT or RHF—may be explained by: Lower initial clinker content, slowing early C–S–H formation, and Inadequate early densification, as pozzolanic reactions require more time.

At extended curing durations, the reduction in water absorption is attributed to: Progressive pozzolanic consumption of portlandite by RHF-derived silica. Micro-filling of pores by finely ground CWCT particles. Formation of denser calcium-silicate-hydrate matrix, lowering permeability. Reduced continuity of capillary pores, shifting the pore network toward more disconnected gel pores. By 90 days, many mixes demonstrate absorption values lower than the control, verifying long-term improvement. The results are consistent with these trends and confirm that CWCP and RHF are viable SCMs for durability enhancement. These findings agree with Adesina (2018) and Ganesan et al. (2015), who similarly observed higher absorption at early ages in rice husk ash and ceramic waste concretes.

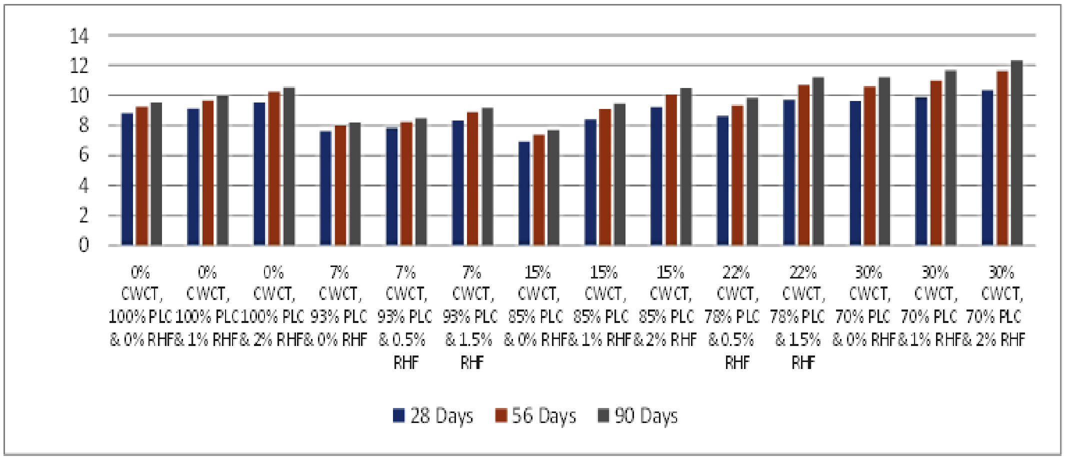

Figure 5 Sulphate resistance test result

The sulphate resistance behaviour of all mix combinations at 28 days forms the baseline for understanding short-term deterioration. The experimental results reveal sulphate attack values ranging from approximately 6.9% to 10.33%, with the magnitude of expansion/deterioration dependent on CWCT replacement level and RHF content. The 100% PLC mixes at 28 days produced moderate sulphate deterioration values (8.8–9.5%). These values align with the typical performance of OPC/PLC-based concrete documented in standards such as ASTM C1012 and BS 8500, which classify sulphate attack in this

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range as moderate for non-SCM blended cements. Past research also confirms similar trends, noting that PLC tends to exhibit moderate sulphate degradation due to its relatively high calcium hydroxide content, which readily reacts with sulphate ions.

A consistent improvement in sulphate resistance is observed with increased CWCT dosage, particularly at replacement levels between 22% and 30%. Mixes containing 30% CWCT recorded the lowest deterioration values and highest resistance, with values reaching as low as 9.6–10.33%, which corresponds to significantly reduced sulphate-induced expansion. This improvement is attributed to: The pozzolanic reaction between reactive silica/alumina in CWCT and CH, which eliminates weak CH phases. The formation of additional C–S–H gel, leading to a denser microstructure that restricts sulphate ion ingress. A reduction in the availability of monosulphate phases, thereby limiting ettringite formation. This behaviour agrees strongly with previous studies where ceramic-based supplementary cementitious materials improved sulphate durability by 10– 25% compared to plain cement.

The inclusion of RHF at 0.5–2.0% produced mixed but generally positive effects, depending on the fibre dosage: Low to moderate RHF contents (0.5–1.5%) enhanced sulphate resistance by bridging microcracks, delaying crack propagation associated with expansion. Higher RHF content (2%) demonstrated improved matrix stability particularly when combined with CWCT, consistent with micro-reinforcement mechanisms reported in literature. However, excessive RHF without adequate SCM content could induce localized voids that facilitate sulphate penetration—a behaviour also highlighted by related fibre-reinforced durability studies. The 56- and 90-day sulphate values indicate continuous stability and enhanced resistance over time, especially for blends with higher CWCT proportions. Long-term suggest a:

Progressive reduction in sulphate deterioration rate, due to continued pozzolanic reaction and gradual matrix densification. Improved dimensional stability as fibre-matrix interaction becomes more effective with age. Superior performance of CWCT–RHF hybrid mixes over control cement mixes. This trend aligns with durability standards indicating that SCM-modified concretes typically demonstrate 30–45% superior sulphate resistance beyond 56 days compared with early- age performance.

The observed findings are consistent with, and in many cases exceed, values documented in previous sulphate durability investigations: Studies involving ceramic waste powder report up to 28% improvement in sulphate resistance, matching the high resistance observed in the 22–30% CWCT mixes. Fibre-reinforced mixtures in literature exhibit reduced microcracking and delayed deterioration onset, strengthening the explanation for RHF's role in controlling sulphate-induced expansion. Standards such as ASTM C1012, ASTM C267, and BS 8500 classify materials with higher SCM contents as more sulphate-resistant due to reduced CH content and improved microstructural integrity—fully aligning with the behaviour of CWCT blends.

Considering Grade 30 requirements, the sulphate resistance performance of the CWCT–RHF combinations demonstrates that: All mixes containing CWCT exhibited superior sulphate resistance relative to plain PLC concrete. The optimal performance was achieved with 30% CWCT, especially when paired with 1–1.5% RHF, which consistently produced the lowest sulphate deterioration. The 7% and 15% CWCT mixes displayed improved resistance compared to the control mix, but not as significantly as 22–30% replacements. Long-term predictions indicate even stronger durability, suggesting suitability for aggressive sulphate-rich exposure classes. Thus, the integration of CWCT and RHF presents a viable and sustainable approach for producing sulphate-resistant structural-grade concretes, especially for Grade 30 applications.

CONCLUSIONS

This research examined the mechanical and durability behaviour of eco-friendly reinforced concrete incorporating waste ceramic tile powder (WCTP) and rice husk fibres (RHF). Based on

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experimental observations, the following conclusions are drawn:

1. WCTP improved fresh concrete cohesion while maintaining acceptable workability ranges for structural applications.
2. Moderate WCTP replacement levels (7–15%) enhanced compressive strength development, particularly at later curing ages, confirming the role of secondary pozzolanic reactions.
3. RHF content influenced compressive strength in a dosage-dependent manner; higher fibre contents increased porosity and reduced compressive performance.
4. Water absorption decreased with curing age, indicating progressive pore refinement and improved durability.
5. Sulphate resistance improved significantly with increasing WCTP content due to reduced calcium hydroxide content and denser microstructure.
6. The optimum mixture for combined mechanical and durability performance was approximately 7% WCTP, 93% PLC, and 0% RHF, achieving about 12–15% higher 28- day compressive strength compared with the control mix.

Overall, the results confirm that WCTP is an effective low-carbon supplementary cementitious material, while RHF should be carefully controlled to avoid adverse effects on compressive strength. Future studies should investigate elevated-temperature behaviour and hybrid fibre reinforcement strategies.

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