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Effect of Rice Husk Ash and Fly Ash on Mechanical Properties of Cement Concrete

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Abstract: Concrete is one of the most widely used construction materials globally, and cement remains its primary binding agent. Yet cement production is one of the more energy-hungry industrial processes we have, and it releases a significant amount of carbon dioxide into the atmosphere as a byproduct. As concerns about environmental sustainability have grown, researchers and engineers have been looking for ways to reduce how much cement goes into concrete without sacrificing the performance that structural applications demand. Two materials that have attracted considerable interest in this regard are Rice Husk Ash (RHA), an agricultural byproduct generated by burning rice husk at controlled temperatures, and Fly Ash (FA), an industrial residue collected from coal-fired power plants. Both are rich in silica and alumina, which gives them pozzolanic properties — meaning they can react with the calcium hydroxide released during cement hydration to form additional calcium silicate hydrate gel, the same compound responsible for concrete's strength and density.

This study investigates the combined effect of RHA and FA as partial replacements for cement in M30 grade concrete. Six replacement levels were examined: 4%, 8%, 12%, 16%, 20%, and 24% by weight of cement, with RHA and FA used together in each mix at specific proportional splits. Standard cube specimens measuring 150 mm x 150 mm x 150 mm were cast and cured for 7 and 28 days. Fresh concrete properties were evaluated through the slump cone test, while hardened concrete properties were assessed through compressive strength testing, water absorption testing, and unit weight measurements.

The results showed that workability decreased gradually as the replacement percentage increased, primarily because RHA has a high surface area and absorbs more water. However, with the addition of a superplasticizer, satisfactory workability was maintained across all mixes. On the strength front, all mixes up to 20% replacement successfully met the M30 target compressive strength of 30 N/mm2 at 28 days. The 4% replacement mix recorded the highest 7-day strength, while the 16% and 20% mixes showed the best overall performance at 28 days, achieving average strengths of 31.2 N/mm2 and 31.6 N/mm2 respectively. The 24% replacement mix fell below the required strength threshold. Water absorption results mirrored this trend, with the 20% mix recording the lowest absorption at both testing ages — 1.64% at 7 days and 1.13% at 28 days — indicating a denser, more durable concrete matrix. Unit weight also peaked at the 16% and 20% replacement levels, further confirming improved compaction and microstructural density.

Based on these experimental findings, the optimum range for partial cement replacement with combined RHA and FA in M30 grade concrete is identified as 16% to 20%. Concrete produced within this range demonstrates adequate structural strength, improved durability, better compaction, and meaningful environmental and economic benefits through reduced cement consumption and effective utilisation of industrial and agricultural waste.

Keywords: Rice Husk Ash, Fly Ash, M30 Concrete, Compressive Strength, Pozzolanic Material, Supplementary Cementitious Material, Sustainable Concrete, Water Absorption, Partial Cement Replacement, IS 10262:2019.

I. INTRODUCTION

A. General Background

Walk onto any construction site in India today and one thing is immediately obvious: concrete is everywhere. It forms the columns and beams of multistorey buildings, the slabs beneath our feet, the bridges that carry our roads over rivers, and the foundations beneath it all. Concrete is, without question, the most widely used construction material in the world, and it has been for over a century. What makes it so versatile — and what keeps us coming back to it — is its ability to be cast into almost any shape while wet, and to develop considerable strength as it hardens. The key ingredient that makes this possible is cement.

But cement comes with a cost that goes beyond its price per bag. The manufacturing process for Ordinary Portland Cement involves heating limestone and clay to extremely high temperatures in large rotary kilns. This calcination process releases carbon dioxide both from the fuel burned to generate the heat and from the chemical decomposition of the limestone itself. Globally, cement production accounts for somewhere between 7% and 8% of all human-generated carbon dioxide emissions — a figure that tends to surprise people when they first encounter it. For a country like India, which is in the middle of a massive infrastructure expansion and is also the world's second largest rice producer, this poses both a challenge and an opportunity.

The challenge is finding ways to reduce the environmental burden of concrete construction. The opportunity lies in two materials that India generates in enormous quantities every year and currently has difficulty disposing of: rice husk ash and fly ash. Rice husk is the protective outer shell removed from rice grains during milling. India produces tens of millions of tonnes of it annually, and much of it is simply burned — either for energy or as waste — generating rice husk ash that is often left to accumulate around mills and cause local environmental problems. Fly ash, meanwhile, is the fine powdery residue captured from the flue gases of coal-fired power stations, which India operates in large numbers. Both materials, when properly processed and proportioned, can partially replace cement in concrete — reducing the demand for virgin cement while actually improving several concrete properties in the process.

This project is motivated by that dual possibility. We set out to examine, through systematic laboratory experimentation, exactly what happens to M30 grade concrete when cement is partially replaced with combinations of rice husk ash and fly ash at progressively higher replacement levels. The investigation covers fresh concrete behaviour, hardened strength development, water absorption characteristics, and unit weight — giving a reasonably complete picture of how these materials influence concrete performance.

B. Problem Statement

The problem this study addresses has two sides to it. On one side sits the environmental and economic cost of cement. Ordinary Portland Cement production is energy intensive, carbon heavy, and increasingly expensive. As construction demand grows — particularly in developing economies like India's — so does pressure on the resources and ecosystems that cement manufacture depends on. There is a genuine and urgent need to find ways to produce concrete that performs adequately with less cement.

On the other side sit two waste streams that have their own disposal problems. Rice husk ash, if not properly managed, creates dust pollution, takes up land, and leaches compounds that can affect local water quality. Fly ash from power plants is generated in such quantities that even with existing reuse pathways, large fractions end up in ash ponds that carry their own environmental risks. Using these materials as supplementary cementitious materials in concrete addresses both problems simultaneously: it reduces cement consumption and provides a productive outlet for materials that would otherwise be waste.

The specific technical problem, however, is that the combined use of RHA and FA in concrete is not yet fully characterised across different proportions and mix conditions. Individually, each material has been studied reasonably well. Together, particularly across the range of 4% to 24% total replacement, the interaction effects on strength, workability, and durability require systematic experimental investigation. That is precisely what this study provides.

C. Objectives

The objectives of this investigation can be summarised as follows:

1) To evaluate the effect of partial cement replacement with RHA and FA, individually identified by proportion, on the mechanical properties of M30 grade concrete.
2) To determine the optimum replacement percentage that achieves the best balance between compressive strength, workability, water absorption, and unit weight.
3) To compare the performance of blended mixes against a conventional control concrete and against each other across 7-day and 28-day testing ages.
4) To assess the workability of fresh concrete at each replacement level, with and without superplasticizer support.
5) To evaluate the durability indicators of the hardened concrete — specifically water absorption and unit weight — and relate them to the compressive strength findings.
6) To draw conclusions about the environmental and economic benefits of using RHA and FA as cement replacements and recommend an optimum mix for practical construction use.

II. LITERATURE SURVEY

A. Review of Published Research

Before undertaking the experimental work, we reviewed a substantial body of published literature on the use of rice husk ash and fly ash in concrete. The review confirmed that both materials have been studied individually and in combination across a range of mix designs, curing conditions, and replacement levels, and that the general direction of findings is consistent even if the precise optimum proportions vary from study to study.

Among the more recent work, Barbhuiya et al. (2025) conducted a comprehensive review concluding that RHA can be effectively used as a partial cement replacement in structural concrete, with improved durability, satisfactory strength, and measurable reductions in environmental impact. Montazeri et al. (2024) offered an important refinement on this picture through a durability-based life cycle assessment that linked RHA dosage to mechanical property gains and service life outcomes, synthesising evidence that properly optimised RHA contents improve both compressive strength and durability while reducing the embodied carbon of the concrete system.

Abdulhussein (2023) reviewed high-volume fly ash use in lightweight aggregate concrete, examining the effects on compressive, tensile, and flexural resistance and exploring strategies to maintain mechanical performance at higher FA replacement levels. Srinath and Ramesh (2023) concluded in their review on sustainable concrete that RHA can enhance mechanical properties and reduce cement consumption when used in optimum proportions, while Sathvik et al. (2022) identified an optimal 25% fly ash replacement level in concrete using manufactured sand, finding that long-term calcium silicate hydrate development from the FA pozzolanic reaction underpins the strength gains observed at later ages.

Going back slightly further, Amran et al. (2021) offered a critical review finding that RHA-based concrete composites can achieve high strength, lower permeability, and enhanced resistance to aggressive environments when the ash is properly processed and used within appropriate dosage ranges. Joel Sam (2020) reviewed both FA and RHA concrete and concluded that optimum replacement levels improve compressive strength while lowering cement usage and carbon emissions. Prakash et al. (2020) added an important observation: blended mixes containing both RHA and fly ash reduced the heat of hydration and showed improved later-age strength compared to either material used alone, which is consistent with the idea that the two materials complement each other — RHA accelerating early strength through its high reactive silica content, FA providing longer-term pozzolanic benefit.

Ramasamy (2019) conducted experimental work on RHA concrete at replacement levels of 5%, 10%, 15%, and 20% in M30 and M60 grade concretes, finding that compressive strength increased at 10% replacement — by 7.07% at 90 days — confirming the pozzolanic activity of well-processed RHA. Magdalene et al. (2015) investigated silica admixture effects on concrete properties, finding that 10% addition optimised strength. Abro (2014) studied RHA as a partial cement substitute at 0%, 5%, 10%, 15%, and 20% replacement, examining both fresh and hardened properties. Katroliya (2013) evaluated combined RHA and FA replacement at proportions up to 25% total, finding measurable effects on physical and mechanical properties. Kadambari (2012) examined M25 grade concrete with combined FA and RHA and Anwar et al. (2011) studied the fundamental fresh and hardened concrete properties of RHA-modified mixes in a foundational study that helped establish the research direction this field has since followed.

B. Summary of Literature Findings

Pulling together the evidence from across the literature, a few consistent findings emerge. Rice husk ash, by virtue of its high amorphous silica content and fine particle size, is a highly reactive pozzolanic material. At replacement levels between 5% and 15%, it consistently improves compressive, tensile, and flexural strength through the formation of additional calcium silicate hydrate gel. Its fine particles fill micro-pores, reducing permeability and improving durability. Beyond about 15 to 20% replacement, however, the high surface area of RHA increases water demand significantly, reducing workability and potentially offsetting the strength gains.

Fly ash behaves somewhat differently. Its spherical particles actually improve the workability of fresh concrete — often described as a ball-bearing effect — making it easier to place and compact. However, fly ash reacts more slowly than RHA, which means early-age strength is typically lower in FA-rich mixes. At 28 days and beyond, though, the pozzolanic contribution of fly ash becomes significant, and concrete with 20 to 30% FA replacement often matches or exceeds the performance of conventional concrete. Optimal fly ash replacement is generally cited in the range of 20% to 30%.

When RHA and FA are used together in a ternary blend, their complementary characteristics produce a synergistic effect: RHA compensates for FA's slow early-age reactivity, while FA improves the workability that RHA alone would reduce. Combined replacement levels in the range of 15% to 30% — typically with RHA contributing 5% to 12% and FA contributing the remainder — have been shown to produce concrete with balanced strength, durability, and workability. These combinations also reduce the carbon footprint of the concrete by replacing a portion of the most energy-intensive ingredient.

III. MATERIALS AND METHODOLOGY

A. Overview of Approach

The methodology followed in this investigation proceeded in a logical sequence: collection and characterisation of raw materials, preparation of rice husk ash through controlled burning, design of the M30 concrete mix, casting of cube specimens at seven different mix proportions (one control and six replacement levels), curing for specified periods, and systematic testing of fresh and hardened concrete properties. All material tests, mix design procedures, and concrete performance evaluations were carried out in accordance with relevant Indian Standard codes to ensure reliability and reproducibility of results.

B. Materials Used

The concrete ingredients used in this investigation were sourced locally and tested to verify their conformance with relevant standards before use. Ordinary Portland Cement of 53 grade (Ultratech Cement) conforming to IS 12269:1987 was used as the primary binder. Its specific gravity was confirmed at 3.15, standard consistency at 32%, initial setting time at 40 minutes, and final setting time at 300 minutes — all within IS code requirements.

Fine aggregate was Narmada River sand passing through a 4.75 mm IS sieve, conforming to Grading Zone II as per IS 383-1970. Its specific gravity was 2.65, fineness modulus 2.65, and water absorption 0.6%. Coarse aggregate consisted of machine-crushed angular stone in two fractions — 20 mm and 10 mm — both with a specific gravity of 2.82 and water absorption of 0.2%. These values confirmed both aggregates met the IS code requirements for use in structural concrete.

Fly ash was sourced from the Relcon RMC Plant at Padgha. It is a fine, powdery residue from coal combustion, rich in silica and alumina, and classified as a Class F pozzolan. Its specific gravity was measured at 2.31, fineness at 18% retained on the 90-micron sieve, and bulk density at 780 kg/m3. Rice husk ash was produced locally from husk collected at Deololi Village Rice Mill. The husk was cleaned, dried, burned under controlled conditions at 400 to 600 degrees Celsius, cooled slowly, ground, and then sieved through a 90-micron sieve to produce a consistent, reactive ash. Its specific gravity was measured at 2.12, fineness at 12% retained on the 90-micron sieve, and bulk density at 480 kg/m3. The lower specific gravity and bulk density of RHA compared to FA and cement reflects its highly porous, cellular particle structure — a characteristic that gives it high pozzolanic reactivity but also contributes to its increased water demand.

CONPLAST SP430 G8 superplasticizer from FOSROC was used at 2% of the cement weight by mass in all mixes to maintain workability as the RHA and FA content increased. Ordinary potable tap water was used for both mixing and curing.

C. Mix Design

The base mix was designed for M30 grade concrete as per IS 10262:2019 and IS 456:2000. The design stipulations were a target mean strength of 38.25 N/mm2 (to account for standard deviation), a maximum water-cement ratio of 0.48, OPC 53 grade cement, 20 mm maximum aggregate size, and moderate exposure conditions. The resulting mix proportions were: Cement = 387.5 kg/m3, Fine Aggregate = 688.51 kg/m3, Coarse Aggregate = 1215.93 kg/m3, and Water = 186 litres/m3, giving a mix ratio of 1:1.78:3.14 with a water-cement ratio of 0.48.

From this base, six replacement mixes were prepared by substituting a portion of the cement with combined RHA and FA. The replacement levels were 4%, 8%, 12%, 16%, 20%, and 24% of the total cement content by weight. Within each level, the split between RHA and FA was maintained such that RHA contributed slightly more than FA, reflecting the principle established in literature that a higher RHA proportion relative to FA maximises the synergistic pozzolanic benefit. The control mix with no replacement was designated CC, and the six blended mixes were designated M1 through M6.

Table 1: Mix Proportions for One Cube Specimen (150 mm x 150 mm x 150 mm)

Mix	Replacement	RHA %	FA %	Cement (kg)	RHA (kg)	FA (kg)	Sand (kg)	Agg. (kg)	Water (L)
CC	0%	0	0	1.44	—	—	2.56	4.52	0.69
M1	4%	2.5	1.5	1.38	0.036	0.022	2.56	4.52	0.69
M2	8%	4.5	3.5	1.32	0.065	0.050	2.56	4.52	0.69
M3	12%	6.5	5.5	1.27	0.094	0.079	2.56	4.52	0.69
M4	16%	8.5	7.5	1.21	0.122	0.108	2.56	4.52	0.69
M5	20%	10.5	9.5	1.15	0.151	0.137	2.56	4.52	0.69
M6	24%	12.5	11.5	1.09	0.180	0.166	2.56	4.52	0.69

D. Specimen Preparation and Curing

A total of 37 cube specimens of 150 mm x 150 mm x 150 mm were cast across the seven mix proportions. The process was carried out with careful attention to consistency so that any differences in results could be attributed to the mix composition rather than to variation in preparation. Moulds were cleaned, assembled, and oiled before use. The cementitious materials (cement, RHA, and FA where applicable), sand, and aggregates were first dry-mixed thoroughly until a uniform colour was achieved, then water premixed with superplasticizer was gradually added and mixing continued until a homogeneous, workable concrete was obtained.

Fresh concrete was placed into the cube moulds in three equal layers, each compacted with at least 35 strokes of a standard tamping rod to remove entrapped air voids. The filled moulds were left undisturbed in the laboratory for 24 hours to allow initial setting. Cubes were then carefully demoulded, inspected for surface defects, and immediately transferred to a clean water curing tank, where they were cured continuously until the day of testing — either 7 or 28 days from the date of casting.

IV. EXPERIMENTAL TESTING

All cube testing was carried out at P.J.D. Scientific Test Lab, an approved materials testing facility equipped with calibrated compression testing machines and standard apparatus for all tests performed.

A. Slump Cone Test

The slump cone test was performed on fresh concrete from each mix to assess workability, following the procedure specified in IS 1199. A standard slump cone (top diameter 100 mm, bottom diameter 200 mm, height 300 mm) was filled with concrete in four equal layers, each tamped 25 times with a standard rod. The cone was then lifted vertically and the slump measured as the difference between the cone height and the highest point of the settled concrete.

B. Compressive Strength Test

Compressive strength was evaluated using a Compression Testing Machine (CTM) following the procedure in IS 516. Cube specimens were removed from the curing tank at 7 and 28 days, surface-wiped, and placed centrally on the machine platform. Load was applied continuously without shock until failure. Compressive strength was calculated as the failure load divided by the loaded area (22,500 mm2 for the 150 mm cube). Three cubes were tested for each mix at each age and the average strength recorded.

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C. Water Absorption Test

After the specified curing period, cube specimens were oven dried at 105 to 110 degrees Celsius for 24 hours, cooled to room temperature, and weighed (W1). The cubes were then fully immersed in clean water for 24 hours, removed, surface-wiped, and weighed again (W2). Water absorption was calculated as (W2 - W1) / W1 x 100%.

D. Unit Weight Test

Density was determined by weighing each cube specimen after wiping off surface moisture and dividing the mass by the known volume of the cube (0.003375 m3). Unit weight in kN/m3 was then calculated by multiplying the density by 9.81.

V. RESULTS AND DISCUSSION

A. Workability — Slump Cone Test

The slump values recorded for each mix are presented in Table 2. The control mix (CC) registered a slump of 72 mm, which is consistent with the medium workability range specified for normal RCC work under IS 456:2000. As the RHA and FA replacement level increased from 4% to 24%, the slump declined progressively from 70 mm down to 56 mm. All mixes still fell within the true slump category, indicating cohesive, workable concrete throughout — an outcome that would not have been achievable without the superplasticizer, which compensated for the increased water demand introduced by RHA's high surface area.

The trend is straightforward to explain. RHA particles are extremely fine and porous, with a cellular microstructure that absorbs water aggressively. As the RHA content increases with each successive replacement level, more of the mix water is drawn into these particles rather than remaining available to lubricate the mix. Fly ash partially counteracts this tendency through its spherical particle shape, which has a known ball-bearing effect on fresh concrete, but the net result across these mixes is a steady, moderate reduction in slump. Importantly, the reduction is not so severe as to create placing or compaction difficulties in practice, particularly with superplasticizer support.

Table 2: Slump Cone Test Results

Mix ID	Replacement Level	Slump Value (mm)	Type of Slump	Workability
CC	Conventional	72	True Slump	Medium
M1	4%	70	True Slump	Medium
M2	8%	68	True Slump	Medium
M3	12%	65	True Slump	Medium
M4	16%	62	True Slump	Medium
M5	20%	60	True Slump	Medium
M6	24%	56	True Slump	Low-Medium

B. *Compressive Strength*

The compressive strength results at 7 and 28 days are summarised in Tables 3 and 4 respectively. The overall pattern is instructive and consistent with what the literature would predict for this class of materials.

At 7 days, the M1 mix (4% replacement) recorded the highest average strength at 19.8 N/mm2, just clearing the 7-day indicative requirement of 19.5 N/mm2. As the replacement level increased through M2 to M6, the 7-day strengths declined modestly. This is entirely expected: at early ages, the pozzolanic reactions of RHA and FA have not yet progressed significantly, so the mix effectively has less cementitious binder available, and early strength is slightly lower. The M6 mix (24% replacement) registered only 16.6 N/mm2 at 7 days — a notable drop that signals that the 24% level may be stretching the capacity of the pozzolanic contribution to compensate for the reduced cement content.

Table 3: Compressive Strength Results at 7 Days

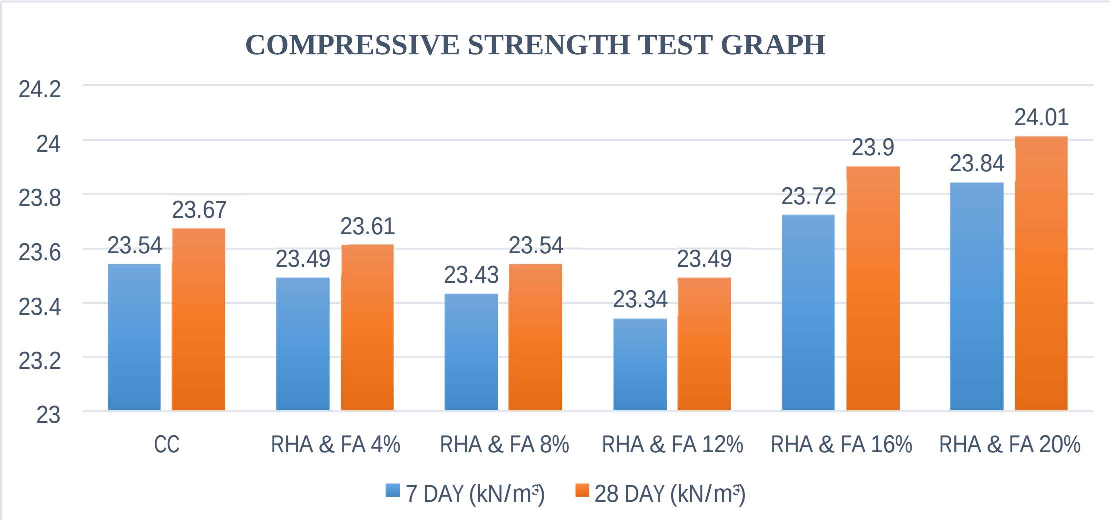
Mix	Replacement	Cube 1 (N/mm²)	Cube 2 (N/mm²)	Cube 3 (N/mm²)	Avg (N/mm²)	Required (N/mm²)	Status
CC	0%	21.5	21.3	21.8	21.5	19.5	PASS
M1	4%	19.6	19.7	20.1	19.8	19.5	PASS
M2	8%	19.2	19.4	19.7	19.4	19.5	FAIL
M3	12%	19.2	19.4	19.3	19.3	19.5	FAIL
M4	16%	18.7	18.9	19.3	19.0	19.5	FAIL
M5	20%	18.9	19.2	18.3	18.8	19.5	FAIL
M6	24%	16.8	16.9	16.1	16.6	19.5	FAIL

The 28-day results tell a significantly different and more positive story. All mixes from M1 through M5 — that is, all replacement levels up to 20% — comfortably met and exceeded the M30 target compressive strength of 30 N/mm2. The 4% replacement mix (M1) achieved the highest average at 33.8 N/mm2, while the 16% and 20% mixes recorded 31.2 N/mm2 and 31.6 N/mm2 respectively. Only the 24% replacement mix (M6) failed at 28 days, averaging 26.4 N/mm2.

Table 4: Compressive Strength Results at 28 Days

Mix	Replacement	Cube 1 (N/mm²)	Cube 2 (N/mm²)	Cube 3 (N/mm²)	Avg (N/mm²)	Required (N/mm²)	Status
CC	0%	35.2	35.6	35.1	35.3	30.0	PASS
M1	4%	33.8	34.1	33.4	33.8	30.0	PASS
M2	8%	32.2	32.4	32.8	32.5	30.0	PASS
M3	12%	31.1	31.6	31.9	31.5	30.0	PASS
M4	16%	31.4	31.3	31.1	31.2	30.0	PASS
M5	20%	31.6	31.1	32.1	31.6	30.0	PASS
M6	24%	26.6	26.1	26.5	26.4	30.0	FAIL

The reason the 28-day picture is so different from the 7-day one comes down to the mechanics of pozzolanic reaction. When cement hydrates in the presence of water, it produces calcium hydroxide as one of the byproducts — a compound that contributes nothing to concrete strength and actually represents a relatively weak component of the hardened cement paste. RHA and FA react with this calcium hydroxide over time, converting it into additional calcium silicate hydrate gel, which is the strength-giving compound in concrete. This reaction is slower than the primary cement hydration, which is why early strengths are lower. But by 28 days, the pozzolanic contribution is well underway, and the denser, more refined pore structure it creates results in concrete that is both stronger and less permeable than the control at the same water-cement ratio.



The reason the 16% and 20% mixes perform so well at 28 days, despite having less cement than the lower-replacement mixes, is that the combined RHA-FA system at these proportions achieves a near-optimal balance. RHA, with its very high reactive silica content, accelerates the early stages of the pozzolanic reaction and helps compensate for the early-age deficit in binder content. FA, with its slower-acting silica and alumina compounds, contributes more substantially at later ages while simultaneously improving particle packing through its spherical morphology. Together at the 16% to 20% range, they produce a concrete matrix with fewer and smaller pores than either material would achieve alone, leading to better mechanical performance overall.

C. *Water Absorption*

The water absorption results across all mixes at 7 and 28 days are shown in Tables 5 and 6. The trend here reinforces the compressive strength findings and offers additional insight into the durability implications of the different replacement levels.

Table 5: Water Absorption Test Results at 7 Days

Mix ID	Replacement	Dry Wt W1 (kg)	Wet Wt W2 (kg)	Water Absorption (%)
CC	Conventional	8.05	8.25	2.48
M1	4%	8.03	8.22	2.37
M2	8%	8.00	8.18	2.25
M3	12%	7.98	8.15	2.13
M4	16%	7.96	8.10	1.76
M5	20%	7.94	8.07	1.64
M6	24%	7.90	8.07	2.15

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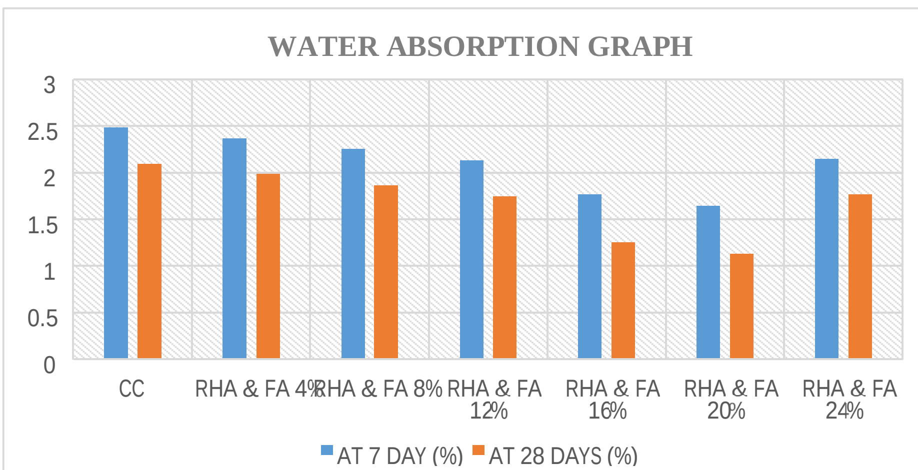
Table 6: Water Absorption Test Results at 28 Days

Mix ID	Replacement	Dry Wt W1 (kg)	Wet Wt W2 (kg)	Water Absorption (%)
CC	Conventional	8.12	8.29	2.09
M1	4%	8.10	8.26	1.98
M2	8%	8.08	8.23	1.86
M3	12%	8.05	8.19	1.74
M4	16%	8.03	8.13	1.25
M5	20%	8.00	8.09	1.13
M6	24%	7.96	8.10	1.76

The conventional control concrete recorded the highest water absorption at both ages — 2.48% at 7 days and 2.09% at 28 days. This is consistent with the fact that plain cement concrete, while certainly functional, does not benefit from the pore-refining action that pozzolanic supplementary materials provide. As the RHA and FA replacement level increased from 4% to 20%, absorption values decreased steadily at both testing ages, reaching a minimum in the M5 mix: 1.64% at 7 days and 1.13% at 28 days. These are meaningfully lower absorption values than the control — a reduction of approximately one-third to one-half depending on the testing age.



The M6 mix (24% replacement) is the exception to the declining trend, showing a slight uptick in absorption compared to M5. This suggests that at 24% replacement, the excessive fine material — particularly the highly porous RHA particles — introduces more internal porosity than the pozzolanic reaction can compensate for, at least within the 28-day testing window. It is entirely possible that continued curing beyond 28 days would reduce absorption further in this mix, given the slow-acting nature of pozzolanic reactions at higher replacement levels, but within the timeframe of this study, 24% replacement represents a point where the trade-off tips away from benefit.

D. Unit Weight

The unit weight results at 7 and 28 days are presented in Tables 7 and 8. Unit weight is a useful indirect indicator of concrete compaction quality and microstructural density. Higher unit weight generally suggests that the concrete matrix has fewer voids and is more uniformly compacted.

Table 7: Unit Weight Test Results at 7 Days

Mix ID	Replacement	Weight (kg)	Density (kg/m³)	Unit Weight (kN/m³)
CC	Conventional	8.10	2400	23.54
M1	4%	8.08	2394	23.49
M2	8%	8.06	2388	23.43
M3	12%	8.03	2379	23.34
M4	16%	8.16	2418	23.72
M5	20%	8.20	2430	23.84
M6	24%	8.00	2370	23.25

Table 8: Unit Weight Test Results at 28 Days

Mix ID	Replacement	Weight (kg)	Density (kg/m³)	Unit Weight (kN/m³)
CC	Conventional	8.14	2412	23.67
M1	4%	8.12	2406	23.61
M2	8%	8.10	2400	23.54
M3	12%	8.08	2394	23.49
M4	16%	8.22	2436	23.90
M5	20%	8.26	2447	24.01
M6	24%	8.04	2382	23.36

The unit weight results show an interesting pattern. At 12% replacement and below, unit weight is slightly lower than the control — reflecting the slightly lower specific gravity of RHA and FA compared to cement. But at 16% and 20% replacement, unit weight rises above the control values, peaking at 23.84 kN/m3 (7 days) and 24.01 kN/m3 (28 days) for the M5 mix. This counterintuitive result — where replacing cement with lighter materials produces denser concrete — is explained by the particle packing effect. The fine RHA and FA particles fill the interstitial spaces between cement grains and aggregate particles more effectively than cement alone, producing a denser overall packing arrangement. The 28-day values are also consistently higher than the 7-day values across all mixes, which reflects the ongoing hydration and pozzolanic reactions progressively filling in the capillary pore network. Again, the 24% mix is the outlier, showing reduced unit weight compared to both M4 and M5, consistent with its lower compressive strength and higher porosity.

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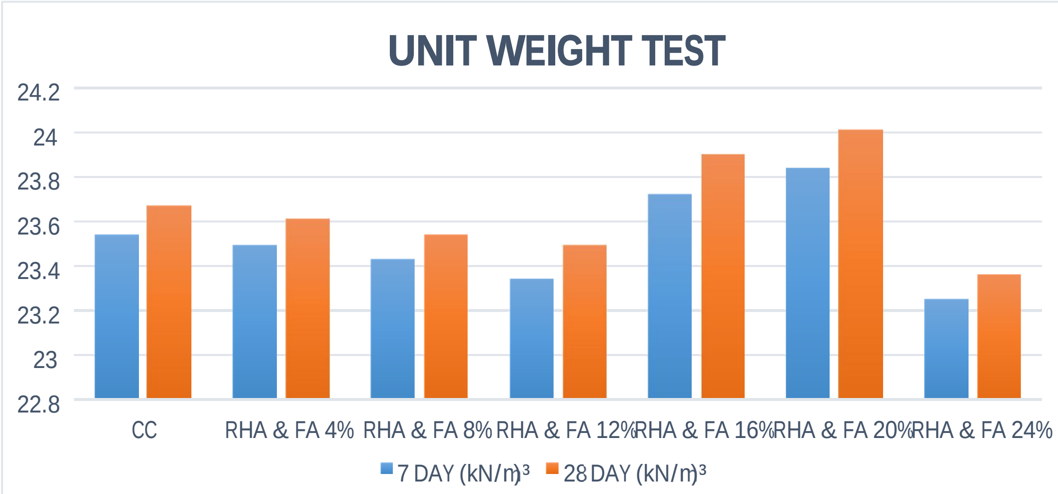

VI. DISCUSSION

A. Overall Performance Assessment

Looking across all four performance indicators together — workability, compressive strength, water absorption, and unit weight — a consistent picture emerges. Mixes containing 16% and 20% total replacement of cement with combined RHA and FA deliver the best overall performance. They meet the M30 strength requirement with a comfortable margin, they show the lowest water absorption values indicating better durability and lower porosity, and they exhibit the highest unit weight indicating denser, better-compacted concrete. They do this while containing notably less cement than the control mix, which is the entire point of the exercise.

The improvement in these mixes is not accidental. It reflects a genuine synergy between the two supplementary materials operating at an effective combined dosage. RHA contributes its highly reactive silica to the pozzolanic reaction with calcium hydroxide, refining the pore structure and densifying the interfacial transition zone between aggregate particles and cement paste. FA contributes more gradually, but its spherical particles improve the packing density of the cementitious fraction and provide a sustained source of reactive silica and alumina that continues contributing to strength and densification well beyond 28 days. The two materials together, in the proportions used in M4 and M5, hit a sweet spot where the sum of their contributions exceeds what either would achieve individually — or what a higher total replacement would achieve if the balance between them were shifted.

B. The 24% Replacement Limit

The failure of the 24% replacement mix to meet the M30 strength target is an important finding and one that has practical implications for engineers considering the use of these materials. It is not that 24% replacement is inherently infeasible — longer curing periods might eventually produce adequate strength — but within the standard 28-day evaluation period that governs most structural concrete acceptance decisions, 24% is simply too much. The reduced cement content provides insufficient calcium hydroxide for the pozzolanic materials to react with, and the excess fine material from RHA introduces porosity that cannot be eliminated without extended curing.

This finding aligns with the general boundary identified in the literature: most studies confirm that combined RHA and FA replacement beyond about 20% to 25% of cement content risks strength deficiency unless the mix is carefully adjusted in other ways — for example, by increasing the superplasticizer dosage, reducing the water-cement ratio further, or using finer, more reactive versions of one or both supplementary materials. None of those adjustments were made in this study, so the finding serves as a realistic practical limit for the materials and conditions used here.

C. Environmental and Economic Significance

Beyond the mechanical performance outcomes, the broader significance of this work lies in what it demonstrates about the potential for sustainable concrete production. At the optimum 20% replacement level, every cubic metre of M30 concrete produced with this mix contains approximately 78 kg less cement than the control mix. Cement production releases roughly 0.9 kg of CO_2 per kilogram of cement produced.

That means each cubic metre of M5 concrete produced instead of conventional concrete avoids approximately 70 kg of carbon dioxide emissions — before accounting for any carbon that might have been released by the disposal or processing of the RHA and FA.

From an economic standpoint, cement is the most expensive ingredient in concrete. Reducing its content by 20% while maintaining strength has a direct and meaningful effect on the cost of production, particularly at the scales at which concrete is consumed in Indian infrastructure construction. The RHA is essentially a waste product that would otherwise need to be disposed of. The fly ash is available at nominal cost from the power plant. Both represent value that is currently being left on the table.

VII. CONCLUSION

This experimental investigation into the combined use of Rice Husk Ash and Fly Ash as partial replacements for cement in M30 grade concrete leads to a set of conclusions that are both technically robust and practically useful.

Workability declined gradually with increasing RHA and FA content, primarily due to the high surface area and water absorption of RHA particles. However, with superplasticizer support at 2% of cement weight, all mixes remained workable and produced true slumps suitable for conventional placement and compaction.

Compressive strength at 7 days was slightly lower in the blended mixes than in the control, reflecting the slow-reacting nature of pozzolanic materials at early ages. By 28 days, however, all mixes up to 20% replacement met and exceeded the M30 target strength of 30 N/mm2, with the 16% and 20% mixes performing particularly well at 31.2 N/mm2 and 31.6 N/mm2 respectively. The 24% replacement mix failed the 28-day strength criterion at 26.4 N/mm2 and should not be used in applications where M30 performance at 28 days is required. Water absorption and unit weight results both supported the strength findings. The 16% and 20% replacement mixes showed the lowest water absorption — indicating reduced porosity and better durability — and the highest unit weight, indicating improved compaction and denser microstructure. These outcomes reflect the combined pozzolanic reaction and particle packing effect of RHA and FA operating together at their most effective combined dosage. Based on the totality of the experimental evidence, the optimum replacement level for combined RHA and FA in M30 grade concrete is 16% to 20% by weight of cement. Concrete produced within this range satisfies structural strength requirements, offers measurably better durability indicators than conventional concrete, and delivers meaningful environmental and economic benefits through reduced cement consumption and productive use of agricultural and industrial waste materials. This range is recommended for practical construction applications where both performance and sustainability are priorities.

VIII. FUTURE SCOPE

Several directions for further work emerge naturally from the findings of this study. The most immediate extension would be to evaluate the same replacement levels in higher-grade concretes — M40, M50, and M60 — where the demands on binder efficiency are greater and the consequences of strength deficiency are more serious. Understanding how RHA and FA perform in high-strength concrete would broaden the applicability of these materials significantly.

On the durability side, the water absorption test used in this study is a relatively simple indicator. More comprehensive durability assessment would involve acid resistance testing, sulphate resistance, chloride penetration depth measurement, carbonation depth, and long-term permeability testing. These tests would provide a much fuller picture of how concrete containing RHA and FA would perform over a realistic service life. It would also be worthwhile to examine the effect of different curing regimes — accelerated curing, steam curing, membrane curing — on the development of strength in these blended mixes. Given that the early-age strength deficit observed in this study is driven by the slow pozzolanic reaction rate, accelerated curing conditions that speed up that reaction could allow higher replacement levels to achieve adequate early strength, expanding the usable range.

Finally, combining RHA and FA with other supplementary materials such as silica fume, ground granulated blast furnace slag, or metakaolin — and potentially with structural fibres — opens up the possibility of high-performance and special-purpose concretes with enhanced properties. Field trials using the optimum mix proportions identified in this study, in applications such as precast elements, road pavements, or low-cost housing construction, would provide the real-world performance validation needed to move these materials from laboratory investigation to widespread practical adoption.

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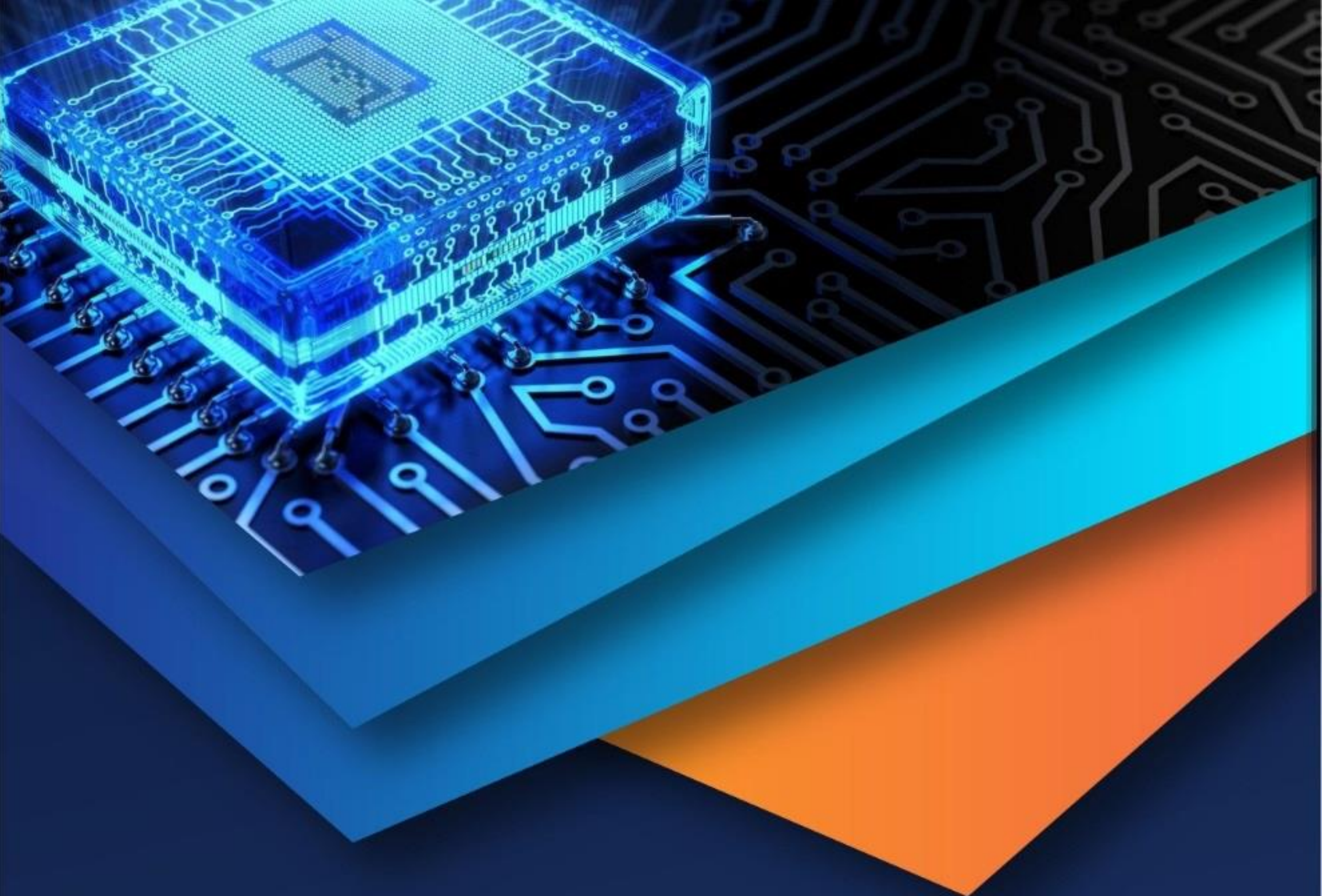

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