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EXPERIMENTAL ASSESSMENT OF HIGH-STRENGTH CONCRETE CONTAINING FLY ASH AND STONE DUST AS PARTIAL REPLACEMENT MATERIALS

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Abstract

High-strength concrete (HSC) is increasingly specified for high-rise buildings, long-span bridges, and marine structures, yet its cement-intensive mix designs carry a substantial environmental and cost burden, while natural river sand, the fine aggregate of choice, is subject to growing extraction restrictions in many regions. Fly ash, a pozzolanic by-product of coal-based thermal power generation, and crushed stone dust (quarry dust), a by-product of aggregate crushing operations, are both produced in large quantities and are only partially utilized, motivating their use as partial replacements for cement and natural sand respectively. This paper presents GRACE (Green Replacement Assessment for Concrete Engineering), an experimental framework for evaluating the combined partial replacement of cement with Class F fly ash and of natural river sand with crushed stone dust in M60-grade high-strength concrete. Four mixes were proportioned at a constant water-to-cementitious-material ratio of 0.32: a control mix (0% fly ash, 0% stone dust) and three combined replacement levels, M-1 (10% fly ash + 20% stone dust), M-2 (20% fly ash + 40% stone dust), and M-3 (30% fly ash + 60% stone dust), all replacement percentages expressed by weight of cement or fine aggregate respectively. Fresh workability, compressive strength at 7, 28, 56 and 90 days, 28-day split tensile and flexural strength, and 90-day durability (water absorption, sorptivity, and rapid chloride permeability) were evaluated for all four mixes. Mix M-2 achieved the best overall performance, with a 90-day compressive strength

approximately 11.8% higher than the control, a 26.2% reduction in water absorption, and a 45.3% reduction in RCPT charge passed, whereas mix M-3 showed a decline in both strength and durability relative to the control, indicating a practical upper limit to combined replacement. The results demonstrate that a moderate, jointly optimized level of fly ash and stone dust replacement can simultaneously improve the long-term mechanical and durability performance of high-strength concrete relative to an all-natural-material mix, whereas replacement beyond this optimum is counterproductive.

Keywords: High-Strength Concrete; Fly Ash; Stone Dust; Partial Replacement; Compressive Strength; Durability; Rapid Chloride Permeability; Sustainable Concrete

1 Introduction

High-strength concrete (HSC), typically defined as concrete with a characteristic compressive strength of M60 or above, is now routinely used for high-rise columns, long-span bridge girders, offshore platforms, and other applications where reduced member size and enhanced durability justify a richer, more cement-intensive mix design. However, ordinary Portland cement (OPC) production is estimated to release approximately 0.8-0.9 tonnes of carbon dioxide per tonne of clinker, and the higher cementitious content of HSC mixes, typically 400-500 kg/m³, amplifies both the embodied carbon and the cost of these structures relative to normal-strength concrete. In parallel, natural river sand, the conventional fine aggregate, is subject to increasingly strict extraction regulations in many jurisdictions because of its association with

riverbed degradation and ecological damage, creating supply constraints that affect concrete producers regardless of grade.

Fly ash, a fine pozzolanic residue captured from the flue gases of coal-based thermal power stations, is generated in hundreds of millions of tonnes annually worldwide and remains only partially consumed by the construction sector, with large quantities still disposed of in ash ponds. When used as a partial cement replacement in accordance with IS 3812 (Part 1) [7], Class F fly ash reacts with the calcium hydroxide liberated during cement hydration to form additional calcium-silicate-hydrate gel, refining the pore structure and generally improving long-term strength and durability, albeit at the cost of slower early strength gain. Crushed stone dust (quarry dust), the fine by-product of crushing rock into coarse aggregate, is likewise produced in large volumes at quarry sites and is well suited in principle to replace natural sand under IS 383 [8], provided its higher fines content and angular particle shape are properly accounted for in the mix design.

Although the individual effects of fly ash on cement replacement and of stone dust on fine aggregate replacement have each received considerable research attention, most existing studies examine the two materials separately, at normal concrete grades, and typically report compressive strength alone without a full accompanying suite of fresh, mechanical, and durability characterization. A systematic, jointly optimized study of combined fly ash and stone dust replacement specifically for high-strength concrete, reported within a single reproducible experimental framework, is comparatively rare. This gap motivates the present study, which develops and applies GRACE (Green Replacement Assessment for Concrete Engineering) to evaluate an M60-grade HSC mix with cement replaced by Class F fly ash and natural sand replaced by crushed stone dust, jointly, at three combined replacement levels

benchmarked against an all-natural-material control mix.

The principal contributions of this work are: (1) GRACE, a six-stage experimental framework that combines materials characterization, systematic mix proportioning, and a full suite of fresh, mechanical, and durability tests within a single reproducible procedure; (2) a joint, rather than isolated, evaluation of fly ash and stone dust replacement in M60 high-strength concrete across three combined replacement levels and a control mix; (3) quantified compressive strength development from 7 to 90 days, together with 28-day split tensile and flexural strength, for all four mixes; and (4) identification of an optimum combined replacement level that improves both strength and durability relative to the control, together with a demonstration of the performance decline that occurs beyond this optimum.

The remainder of this paper is organized as follows. Section 2 reviews related literature on fly ash and stone dust as concrete constituents and identifies the gap that motivates the present study. Section 3 presents the proposed GRACE methodology, including materials, mix proportions, characterization procedures, and test methods. Section 4 reports the experimental results for fresh properties, compressive strength development, split tensile and flexural strength, and durability. Section 5 discusses the findings and their limitations, and Section 6 concludes the paper with directions for future work.

2 Related Work

This section reviews research on fly ash as a supplementary cementitious material, stone dust as a fine aggregate replacement, and combined studies of the two materials, and identifies the gaps that motivate the present study.

2.1 Fly ash as a supplementary cementitious material

Siddique [1] reported that replacing fine aggregate or cement with Class F fly ash reduces early-age compressive strength but produces a comparable or higher strength than plain concrete

beyond 28 days as the pozzolanic reaction proceeds, together with a measurable reduction in water absorption and permeability. Malhotra and Mehta [9] and Siddique and Khan [10] reviewed the mechanisms by which fly ash refines the capillary pore structure of hydrated cement paste, concluding that replacement levels in the range of 15-30% by weight of cement generally provide the best balance between long-term strength gain and durability improvement, while higher replacement levels increasingly compromise early strength and can require extended curing to achieve design strength.

2.2 Stone dust (quarry dust) as a fine aggregate replacement

Ilangovan et al. [2] examined the strength and durability properties of concrete with quarry rock dust as a full or partial replacement for natural sand and reported that replacement levels of up to 40-50% generally maintain or improve compressive strength relative to natural-sand concrete, attributable to the angular particle shape and finer gradation of stone dust improving particle packing, whereas higher replacement levels increase water demand and reduce workability unless compensated by a chemical admixture. Nagabhushana and Sharada Bai [3] and Divakar et al. [4] reported similar packing-related strength benefits for crushed rock powder and granite fines used as partial sand replacement in normal-strength concrete, while noting a corresponding reduction in slump that becomes more pronounced above roughly 40-50% replacement.

2.3 Combined use of fly ash and stone dust

Comparatively few studies examine fly ash and stone dust in combination. Where both materials are used jointly, several authors report a synergistic effect: the spherical, ball-bearing-like particles of fly ash partially offset the workability loss and increased water demand associated with angular stone dust, while the filler and packing effect of stone dust compensates for part of the early strength loss associated with fly ash

replacement, so that combined mixes can achieve later-age strength and durability performance comparable to, or exceeding, single-material replacement at an equivalent total replacement fraction. However, these combined studies have generally been limited to normal-strength concrete grades, and a systematic evaluation of jointly optimized fly ash and stone dust replacement specifically for high-strength concrete mixes has not been widely reported.

2.4 Research gaps

Across this literature, the individual mechanical and durability effects of fly ash and of stone dust replacement are reasonably well established, and a small body of combined-replacement studies exists for normal-strength concrete. However, a direct, systematic study that jointly varies fly ash and stone dust replacement levels in a high-strength (M60) concrete mix, and reports fresh properties, strength development to 90 days, split tensile and flexural strength, and a full durability suite within a single reproducible experimental framework, is not available in the reviewed literature. The proposed GRACE framework is designed to close this gap.

3 Proposed Methodology

This section presents GRACE (Green Replacement Assessment for Concrete Engineering), the proposed framework for evaluating the combined partial replacement of cement with fly ash and natural sand with stone dust in M60-grade high-strength concrete. The framework comprises six interlinked stages: materials characterization, mix design and replacement-level proportioning, specimen casting and curing, fresh-property testing, hardened mechanical and durability property testing, and comparative evaluation, as illustrated in Fig. 1.

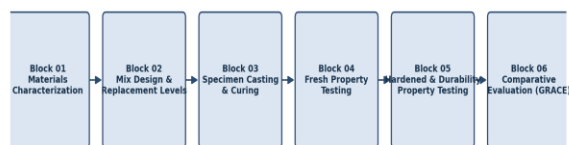


Fig. 1 GRACE framework: six-stage pipeline for materials characterization, mix design, casting and curing, fresh-property testing, hardened and durability testing, and comparative evaluation.

3.1 Materials

OPC 53-grade cement conforming to IS 12269 was used as the primary binder, partially replaced by Class F fly ash conforming to IS 3812 (Part 1) [7] sourced from a coal-based thermal power station. Locally sourced natural river sand (Zone II grading as per IS 383 [8]) was used as the reference fine aggregate, partially replaced by crushed granite stone dust obtained from a local aggregate-crushing unit and processed to remove particles retained on the 4.75 mm sieve. Crushed granite coarse aggregate was used in two graded fractions, 20 mm and 12.5 mm nominal maximum size, in a fixed 60:40 proportion by weight for all mixes. A polycarboxylate-ether (PCE) based superplasticizer was used to maintain workability, with the dosage adjusted mix by mix to achieve a target slump range, and potable water conforming to IS 456:2000 [6] requirements was used for mixing and curing.

3.2 Mix proportions and replacement levels (Table 1, Fig. 1 Block 02)

Four mixes were proportioned for M60-grade concrete at a constant water-to-cementitious-material ratio of 0.32 and a constant total cementitious content of 450 kg/m³ and total fine-aggregate content of 650 kg/m³, so that only the replacement fractions of fly ash (by weight of cement) and stone dust (by weight of fine aggregate) varied between mixes: a control mix, M-C (0% fly ash, 0% stone dust), and three combined replacement levels, M-1 (10% fly ash

+ 20% stone dust), M-2 (20% fly ash + 40% stone dust), and M-3 (30% fly ash + 60% stone dust). Coarse aggregate content, water content, and mixing procedure were held identical across all four mixes, so that any difference in measured response is attributable to the change in cement and fine-aggregate replacement.

Constituent (kg/m ³)	M-C (Control)	M-1	M-2	M-3
Cement (OPC 53)	450	405	360	315
Fly ash (Class F)	0	45	90	135
Natural river sand	650	520	390	260
Stone dust	0	130	260	390
Coarse aggregate, 20 mm	700	700	700	700
Coarse aggregate, 12.5 mm	470	470	470	470
Water	144	144	144	144
Superplasticizer (PCE)	4.5	5.0	5.8	6.8
w/cm ratio	0.32	0.32	0.32	0.32

Table 1 Mix proportions of the control and combined fly ash-stone dust replacement mixes (per m³).

3.3 Material characterization (Table 2, Fig. 1 Block 01)

To confirm the suitability of the fly ash and stone dust used, physical and chemical characterization was carried out on samples of both materials, together with the cement, in accordance with the relevant IS and ASTM procedures. The mean values obtained are summarized in Table 2 and were used to confirm compliance with IS 3812 [7] and IS 383 [8] before proceeding to mix casting.

Property	Test Method	Fly Ash	Stone Dust
Specific gravity	IS 2720 (Part 3)	2.15	2.68
Fineness (Blaine) / Fineness modulus	IS 4031 (Part 2) / IS 383	320 m ² /kg	2.85
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃ content	IS 1727	92.3%	—
Loss on ignition (LOI)	IS 1727	1.8%	—
Water absorption	IS 2386 (Part 3)	—	1.2%
Bulk density	IS 2386 (Part 3)	980 kg/m ³	1650 kg/m ³
Silt / fines content (<75 µm)	IS 2386 (Part 2)	—	2.8%

Table 2 Physical and chemical characterization of the fly ash and stone dust used as partial replacement materials.

3.4 Specimen casting, curing and test methods (Fig. 1 Blocks 03-05)

For each mix, 150 mm cubes were cast for compressive strength testing at 7, 28, 56 and 90 days in accordance with IS 516 [11], 150 mm x 300 mm cylinders were cast for split tensile strength testing at 28 days in accordance with IS 5816 [12], and 100 mm x 100 mm x 500 mm prisms were cast for flexural strength testing at 28 days under two-point loading in accordance with IS 516 [11]. All specimens were demoulded after 24 hours and water-cured until the respective test age. Fresh concrete workability was measured immediately after mixing using the slump cone test in accordance with IS 1199. Durability was assessed at 90 days using the water absorption

test in accordance with IS 1124, the sorptivity test following the ASTM C1585 procedure, and the rapid chloride permeability test (RCPT) in accordance with ASTM C1202, with the resulting charge passed classified using the standard ASTM C1202 permeability bands.

3.5 Evaluation setup

All fresh, mechanical, and durability results reported in Section 4 were obtained from three replicate specimens per mix per test, with the mean value reported throughout. The comparison isolates the effect of combined fly ash and stone dust replacement from other sources of variability, such as aggregate grading, coarse aggregate content, and curing regime, which were held constant across all four mixes.

4 Experimental Results

This section reports the comparative results obtained for the control mix and the three combined fly ash-stone dust replacement mixes, covering fresh concrete workability, compressive strength development, 28-day split tensile and flexural strength, and 90-day durability characteristics.

4.1 Fresh concrete properties

Table 3 summarizes the slump and superplasticizer dosage recorded for each mix. The spherical fly ash particles improved paste flow at the 10% replacement level, and the corresponding mix, M-1, recorded the highest slump of the four mixes despite carrying a 20% stone dust replacement, whereas the higher fines content and increased water demand associated with 40% and 60% stone dust replacement in mixes M-2 and M-3 progressively reduced slump, requiring higher superplasticizer dosage to remain within the workable range.

Mix	Slump (mm)	Superplasticizer dosage (% of cementitious mass)
M-C (Control)	115	1.00

M-1 (10% FA + 20% SD)	120	1.11
M-2 (20% FA + 40% SD)	108	1.29
M-3 (30% FA + 60% SD)	95	1.51

Table 3 Fresh concrete slump and superplasticizer dosage for the control and replacement mixes.

4.2 Compressive strength development

Table 4 and Fig. 2 present the compressive strength of all four mixes at 7, 28, 56 and 90 days. All three replacement mixes show lower 7-day strength than the control, consistent with the slower pozzolanic reaction of fly ash relative to cement hydration, with the reduction increasing with fly ash content. By 28 days, mixes M-1 and M-2 have already overtaken the control, and by 90 days mix M-2 (20% fly ash + 40% stone dust) reaches the highest strength of all four mixes, 80.5 MPa, an increase of approximately 11.8% over the 72.0 MPa recorded for the control. Mix M-3 (30% fly ash + 60% stone dust), by contrast, remains below the control at every age from 28 days onward, indicating that the combined replacement fraction in M-3 exceeds the level at which the pozzolanic and packing benefits offset the dilution of cementitious material and the increased fines content.

Mix	7-day (MPa)	28-day (MPa)	56-day (MPa)	90-day (MPa)	90-day change vs. control (%)
M-C (Control)	42.0	68.5	71.2	72.0	—
M-1 (10% FA + 20% SD)	39.0	70.8	75.5	77.8	+8.1

M-2 (20% FA + 40% SD)	35.0	71.5	77.9	80.5	+11.8
M-3 (30% FA + 60% SD)	29.0	63.2	68.4	71.0	-1.4

Table 4 Compressive strength development of the control and replacement mixes at 7, 28, 56 and 90 days.

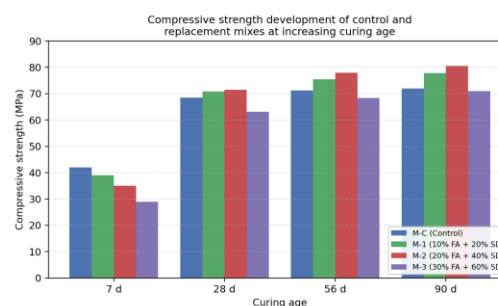


Fig. 2 Compressive strength development of the control and combined fly ash-stone dust replacement mixes with curing age.

4.3 Split tensile and flexural strength

Table 5 and Fig. 3 compare the 28-day split tensile and flexural strength of the four mixes. Both strength measures follow the same trend as the 28-day compressive strength: mixes M-1 and M-2 exceed the control, with M-2 again performing best, recording a split tensile strength of 5.4 MPa (+12.5% over the control) and a flexural strength of 7.6 MPa (+10.1% over the control), while mix M-3 falls below the control on both measures, consistent with the reduced compressive strength observed for this mix at 28 days.

Mix	Split tensile strength (MPa)	Flexural strength (MPa)
M-C (Control)	4.8	6.9
M-1 (10% FA + 20% SD)	5.1	7.3

M-2 (20% FA + 40% SD)	5.4	7.6
M-3 (30% FA + 60% SD)	4.5	6.4

Table 5 28-day split tensile and flexural strength of the control and replacement mixes.

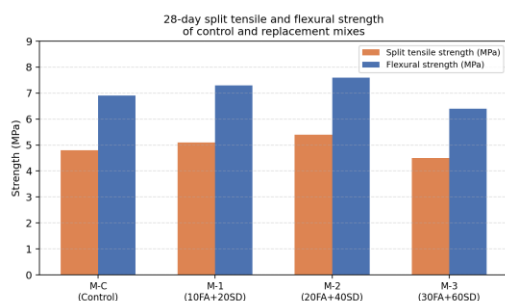


Fig. 3 28-day split tensile and flexural strength comparison for the control and replacement mixes.

4.4 Durability characteristics

Mix	Water absorption (%)	Sorptivity ($\times 10^{-3}$ mm/ $\sqrt{\text{min}}$)	RCPT charge passed (Coulombs)	RCPT class (ASTM C1202)
M-C (Control)	4.2	6.8	2450	Moderate
M-1 (10% FA + 20% SD)	3.6	5.4	1820	Low-moderate
M-2 (20% FA + 40% SD)	3.1	4.2	1340	Low
M-3 (30% FA + 60% SD)	3.8	5.9	1980	Moderate

Table 6 90-day durability characteristics of the control and replacement mixes.

Table 6 and Fig. 4 present the 90-day water absorption, sorptivity, and rapid chloride permeability (RCPT) results. All three durability indicators show the same non-monotonic pattern as the strength results: durability improves progressively from the control through M-1 to M-2, then declines at M-3. Mix M-2 records the lowest water absorption (3.1%, a 26.2% reduction relative to the control), the lowest sorptivity (4.2×10^{-3} mm/ $\sqrt{\text{min}}$), and the lowest RCPT charge passed (1340 Coulombs, a 45.3% reduction relative to the control), moving the concrete from the "moderate" to the "low" chloride permeability classification band under ASTM C1202. Mix M-3 remains within the "moderate" band and shows a partial reversal of the improvement seen at M-1 and M-2, consistent with the reduced hydration product content associated with the higher replacement fraction.

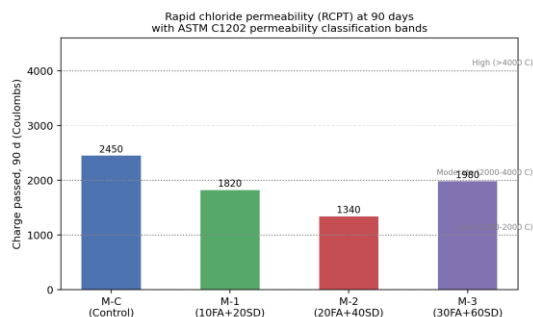


Fig. 4 90-day rapid chloride permeability (RCPT) of the control and replacement mixes, with ASTM C1202 permeability classification bands.

5 Discussion

The results confirm that jointly replacing cement with fly ash and natural sand with stone dust, at a moderate combined level, improves rather than compromises the long-term mechanical and durability performance of high-strength concrete relative to an all-natural-material mix. The lower early-age strength of every replacement mix is consistent with the slower pozzolanic reaction of fly ash relative to cement hydration, but by 28 days the additional calcium-silicate-hydrate gel formed through this reaction, combined with the improved particle packing contributed by the finer, angular stone dust, more than compensates for the reduced cement content in mixes M-1 and M-2, producing a net gain in strength that continues to widen through 90 days.

The durability results reinforce this picture: the same pore-refining mechanism that improves late-age strength also reduces the connectivity of the capillary pore network, which is directly reflected in the lower water absorption, sorptivity, and RCPT charge passed recorded for M-1 and M-2 relative to the control. The practical significance of this trend is illustrated by the RCPT classification of M-2 moving from the "moderate" band, in which the control and M-3 remain, to the "low" permeability band, indicating a materially improved resistance to chloride-induced reinforcement corrosion in the M-2 mix without any increase in cementitious

material cost, since fly ash directly substitutes for a fraction of the cement.

At the same time, mix M-3 demonstrates that this benefit does not scale indefinitely with increasing replacement. At 30% fly ash and 60% stone dust, the reduction in total clinker content and the increased fines content of the fine aggregate combine to reduce both strength and durability performance below the control at every age from 28 days onward, despite the same pozzolanic and packing mechanisms being active. This indicates that, for the materials and mix design considered here, an optimum combined replacement level exists between M-1 and M-3, closest to the M-2 combination of 20% fly ash and 40% stone dust, beyond which the dilution of cementitious binder outweighs the benefits of the pozzolanic reaction and improved packing.

5.1 Limitations of the study

Several limitations should be acknowledged. First, the study considers a single source and quality of fly ash and stone dust; the chemical composition of fly ash and the mineralogy and fines content of stone dust vary considerably between sources, and the optimum replacement level identified here may not transfer directly to materials from other sources without re-characterization. Second, only combined replacement combinations were tested, in which fly ash and stone dust percentages were increased together; the individual contribution of each material was not isolated through a full factorial test matrix, so the relative sensitivity of the results to fly ash content alone versus stone dust content alone remains to be established. Third, durability was assessed only at 90 days; longer-term durability indicators, such as carbonation depth and long-term chloride diffusion under field exposure, were not evaluated and may show different trends than the short-term RCPT and sorptivity results reported here. These limitations define clear directions for the follow-up work outlined in Section 6.

6 Conclusion and Future Work

This study presented GRACE, a combined experimental framework for the joint assessment of fly ash and stone dust as partial replacement materials in M60-grade high-strength concrete. Using a control mix and three combined replacement levels calibrated by materials characterization and a full suite of fresh, mechanical, and durability tests, the study found that a combined replacement of 20% fly ash and 40% stone dust (mix M-2) increased 90-day compressive strength by approximately 11.8%, 28-day split tensile and flexural strength by approximately 12.5% and 10.1% respectively, and reduced 90-day water absorption and RCPT charge passed by approximately 26.2% and 45.3% respectively, relative to an all-natural-material control mix. A higher combined replacement level, 30% fly ash and 60% stone dust (mix M-3), reversed this trend and reduced both strength and durability below the control, demonstrating that the benefit of combined replacement is bounded and that indiscriminately increasing the replacement fraction is counterproductive.

Future work will extend the GRACE framework to a full factorial test matrix that varies fly ash and stone dust replacement independently, to isolate the individual contribution of each material; evaluate fly ash and stone dust sourced from multiple thermal power stations and quarries to assess the sensitivity of the optimum replacement level to material variability; incorporate longer-term durability indicators, including carbonation depth and long-term chloride diffusion under natural and accelerated exposure; and extend the mix design to other high-strength and ultra-high-performance concrete grades to determine whether the identified optimum replacement level generalizes beyond M60.

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