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PARTIAL REPLACEMENT OF CEMENT BY SILICA FUMES IN RAC FOR SUSTAINABLE DEVELOPMENT

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Abstract

The present study evaluates the use of silica fume as a partial cement replacement and recycled concrete aggregate (RCA) as a partial coarse-aggregate replacement in concrete intended for more resource-efficient construction. The experimental programme documented in the project report considered silica-fume replacement levels of 5, 10, 15 and 20% by mass of cement and, in a second series, RCA contents of 5, 10, 15 and 20% used together with 10% silica fume. Compressive strength was measured at 7, 14 and 28 days using 150 mm cubes. The control concrete recorded a reported 28-day average compressive strength of 38 MPa. Silica-fume mixes at 10 and 15% each reached 32 MPa at 28 days, equivalent to 84.2% of the reported control strength, whereas 5 and 20% silica fume reached 28 MPa. In the combined series, 10% silica fume with 5, 10, 15 and 20% RCA produced reported 28-day strengths of 31.9, 30.8, 30.0 and 29.0 MPa, respectively. The results therefore indicate that moderate silica-fume dosage can partly compensate for strength loss associated with recycled aggregate, while increasing RCA content progressively reduces compressive strength in the tested range. The findings are consistent with published literature describing the higher porosity and water absorption of RCA and the pore-refining, pozzolanic contribution of silica fume. Because the source project contains a few internal inconsistencies in concrete-grade designation and one narrative conclusion, this paper retains the tabulated laboratory values as the primary dataset and explicitly identifies items requiring verification before external submission. The study supports continued development of low-impact concrete using combined supplementary cementitious materials and recycled aggregates, with future work recommended on durability, statistical replication, micro-structure and life-cycle performance.

Keywords: silica fume; recycled concrete aggregate; sustainable concrete; compressive strength; cement replacement; construction and demolition waste

1. Introduction

Concrete production consumes large quantities of natural aggregate and Portland cement. At the same time, demolition and reconstruction activities generate substantial volumes of concrete debris. Reprocessing suitable concrete waste as recycled concrete aggregate (RCA) can reduce landfill demand and conserve natural aggregate resources, although the residual adhered mortar on RCA commonly increases porosity and water absorption and can reduce mechanical performance relative to natural aggregate concrete [1,2].

Silica fume (SF), an ultrafine silicon-rich by-product of the silicon and ferrosilicon industries, is widely used as a supplementary cementitious material. Its small particle size contributes a filler effect, while its high amorphous silica content reacts pozzolanically with calcium hydroxide to form additional calcium-silicate-hydrate (C-S-H). Contemporary reviews report that appropriate

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SF dosages can improve compressive strength and permeability-related properties, whereas excessive replacement may reduce workability or strength depending on water-binder ratio and mixture design [3,4].

The combined use of RCA and SF is therefore technically attractive: RCA diverts construction and demolition waste from disposal, while SF can densify the cementitious matrix and potentially improve the weaker interfacial transition zones associated with recycled aggregate. Recent experimental and optimization studies have shown that supplementary cementitious materials can mitigate some adverse effects of RCA, but performance remains strongly dependent on replacement level, source aggregate quality, moisture condition, curing and mixture proportions [5,6].

The project on which this manuscript is based investigated silica-fume replacement of cement at 5-20% and partial replacement of natural coarse aggregate by RCA at 5-20%, with the RCA series incorporating 10% SF. The project objective was primarily to assess compressive strength and identify practical replacement ranges that could support sustainable development without unacceptable loss of mechanical performance. The present paper restructures those project findings into a journal-style manuscript, compares them with standard peer-reviewed literature and recalculates selected performance indicators directly from the reported tables.

2. Literature Review and Research Context

2.1 Recycled concrete aggregate

RCA consists of natural aggregate particles with varying amounts of adhered old mortar. This composite character distinguishes RCA from virgin stone: the old mortar generally has lower density, greater porosity and higher absorption, and crushing may introduce microcracks. Safiuddin et al. [1] and Wang et al. [2] synthesized extensive evidence showing that these characteristics affect workability, density, elastic modulus, compressive strength, shrinkage and durability. Qasim et al. [7] further reported systematic strength and workability changes as coarse natural aggregate was progressively replaced by recycled aggregate.

The engineering significance of RCA is not limited to compressive strength. Water absorption influences effective water-binder ratio; residual mortar can create additional interfacial transition zones; and variability in the parent concrete introduces greater material scatter. Therefore, the percentage of replacement cannot be interpreted independently of aggregate preprocessing, moisture conditioning and mixture design. Durability-focused reviews emphasize that reduction of porosity, removal or strengthening of adhered mortar, and optimized mixing procedures can improve performance [8,9].

2.2 Silica fume as a supplementary cementitious material

Silica fume has a particle size substantially finer than Portland cement and provides both physical packing and chemical benefits. The filler effect improves particle packing, while the pozzolanic reaction consumes calcium hydroxide and produces additional C-S-H, refining capillary pores. Reviews published in Construction and Building Materials, Journal of Materials Research and Technology and Case Studies in Construction Materials consistently report improvements in strength and resistance to fluid ingress over suitable dosage ranges [3,4,10].

The optimum SF content is not universal. A recent review in Construction and Building Materials reported that optimum mechanical-property ranges are often around 7.5-12% but depend on mixture parameters [3], whereas another systematic review identified broader optimum ranges across the surveyed literature [10]. These differences reinforce the need for project-specific testing rather than adoption of one universal percentage. Excess SF can increase water demand, reduce workability and, if insufficient cementitious balance or dispersion is available, reduce measured strength.

2.3 Combined RCA-SF systems and research gap

The use of SF in recycled aggregate concrete is especially relevant because the denser paste produced by SF can improve interfacial zones and compensate partly for the porous recycled particles. Habibi et al. [5] demonstrated through response-surface analysis that combinations of recycled aggregate and supplementary cementitious materials can be optimized simultaneously for mechanical and durability responses. Broader sustainability studies similarly show that recycled aggregates and cement-replacement materials can reduce raw-material consumption and waste generation, but environmental benefit is case-specific and should ideally be assessed over the mixture's service life [6,11].

The specific research need addressed here is an experimentally simple, locally reproducible assessment of compressive-strength response when silica fume is used at several cement-replacement levels and when increasing RCA contents are combined with a fixed 10% SF dosage. Such data are useful for screening promising combinations before undertaking more expensive durability and microstructural investigations.

2.4 Synthesis of selected journal evidence

Reference	Material focus	Key relevance to present study
Safiuddin et al. [1]	RCA concrete review	Documents higher absorption/porosity of RCA and effects on fresh, mechanical and durability properties.
Wang et al. [2]	Comprehensive RA/RAC review	Explains residual mortar, added ITZs, strength, shrinkage and long-term performance mechanisms.
CBM review [3]	Silica-fume concrete	Reports that optimum SF content is mixture-dependent and excessive dosage can adversely affect properties.
JMRT review [4]	Silica fume in sustainable concrete	Summarizes mechanical, durability and microstructural roles of SF.
Habibi et al. [5]	RAC + SF + GGBFS	Shows multi-variable optimization of recycled aggregate with supplementary cementitious materials.
Qasim et al. [7]	Progressive RCA replacement	Provides recent experimental evidence on workability and strength changes with increasing RCA.
Zheng et al. [8]	RAC durability review	Highlights high porosity, water absorption and microcracks as key durability challenges.
Berndt [12]	RCA + SCM concrete	Shows that supplementary cementitious materials can offset part of RCA-related performance loss.

Table 1. Literature synthesis supporting the experimental interpretation.

Collectively, the journal evidence suggests three propositions that guide interpretation of the present data. First, increasing untreated RCA generally creates a strength and durability penalty because of the old mortar and additional interfaces. Second, SF can enhance matrix density and later-age performance, but the optimum replacement percentage depends on water-binder ratio, cement chemistry, curing and workability control. Third, sustainability optimization requires simultaneous consideration of mechanical performance, durability and environmental impact rather than maximizing one replacement percentage in isolation.

3. Experimental Programme

3.1 Materials

The project used Portland cement, fine aggregate, natural coarse aggregate, recycled coarse aggregate obtained from crushed concrete waste, water and silica fume. The source report records cement specific gravity of 3.14, standard consistency of 34%, initial setting time of 48 min, final setting time of 260 min and fineness residue of 6.5%. For aggregates, the reported coarse-aggregate bulk densities were 1498 kg/m³ (loose) and 1711 kg/m³ (compacted), aggregate impact value was 17.30%, crushing strength was reported as 22.06 MPa, and specific gravity was 2.75. Fine aggregate specific gravity was also reported as 2.75, with water absorption of 0.82% and water content of 3.21%.

Material / property	Reported value
Cement specific gravity	3.14
Standard consistency	34%
Initial setting time	48 min
Final setting time	260 min
Cement fineness	6.5%
Coarse aggregate specific gravity	2.75
Fine aggregate specific gravity	2.75
Coarse aggregate water absorption	0.27%
Fine aggregate water absorption	0.82%
Aggregate impact value	17.30%

Table 2. Selected material properties reported in the project laboratory record.

3.2 Mix variables and specimen preparation

The experimental matrix had two principal series. Series S varied silica-fume replacement of cement at 0, 5, 10, 15 and 20%. Series R fixed silica fume at 10% and varied RCA replacement of natural coarse aggregate at 5, 10, 15 and 20%, with the plain control retained for comparison. The project report states that 45 standard cubes of 150 × 150 × 150 mm were cast and water-cured. Three individual compressive-strength readings (C1-C3) are tabulated for each age/mix combination, together with an average value.

Series	Cement replacement by SF	Coarse aggregate replacement by RCA	Test ages
Control	0%	0%	7, 14, 28 d
S5	5%	0%	7, 14, 28 d
S10	10%	0%	7, 14, 28 d
S15	15%	0%	7, 14, 28 d
S20	20%	0%	7, 14, 28 d
R5	10%	5%	7, 14, 28 d
R10	10%	10%	7, 14, 28 d
R15	10%	15%	7, 14, 28 d
R20	10%	20%	7, 14, 28 d

Table 3. Experimental variables reconstructed from the source project.

3.3 Mix-design basis and compressive-strength testing

The source report describes a design-mix procedure based on Indian Standards and discusses target mean strength, water-cement ratio, water demand, cement content, aggregate proportions and trial mixes. It identifies the designed concrete as M35 in the mix-design section and conclusion. Cubes were tested in a compression testing machine after the prescribed curing ages. Compressive strength was evaluated from the failure load divided by the loaded area of the standard cube.

$$f\_c = P / A$$

where f_c is cube compressive strength (N/mm^2 or MPa), P is the recorded failure load (N), and A is the loaded area (mm^2). The present manuscript uses the average strengths reported in the project tables for comparative analysis.

3.4 Data-integrity note

The project documentation contains internal inconsistencies that should be resolved against original laboratory sheets before journal submission. The mix-design section and conclusion identify M35 concrete, while one paragraph in the results chapter refers to M30. In addition, one control 14-day row contains individual values inconsistent with its stated average, and the project conclusion states that 10-15% SF retains about 91% of control strength whereas the tabulated 28-day values (32 MPa versus 38 MPa) give 84.2%. To avoid introducing unsupported corrections, the present paper treats the tabulated average strength values as the primary dataset and reports recalculated percentages transparently.

4. Results

4.1 Effect of silica fume replacement

SF replacement	7-day (MPa)	14-day (MPa)	28-day (MPa)	28-day retention
0%	20	30	38	100.0%
5%	10	15	28	73.7%
10%	11	20	32	84.2%
15%	11	20.5	32	84.2%

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SF replacement	7-day (MPa)	14-day (MPa)	28-day (MPa)	28-day retention
20%	11	20.5	28	73.7%

Table 4. Reported average compressive strength for silica-fume replacement series.

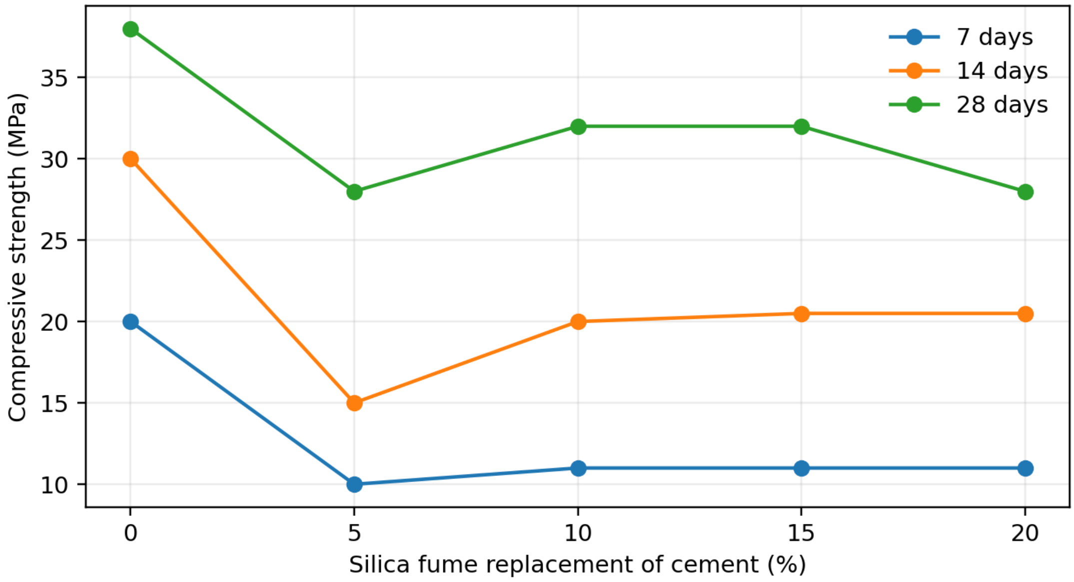

Figure 1. Strength development with silica-fume replacement, based on reported average values.

At 28 days the control concrete reached 38 MPa. Replacement with 5% SF reduced the reported average to 28 MPa. Increasing SF to 10% increased the 28-day strength to 32 MPa, and the same value was reported at 15% SF. At 20% SF the average again reduced to 28 MPa. Within this experimental dataset, therefore, 10-15% SF represents the best-performing range among the replacement mixtures, although neither equalled the control strength.

The early-age results are lower for all SF mixtures than the control. This trend can be rationalized by dilution of Portland cement and the time-dependent contribution of the pozzolanic reaction. The increase from 5% to 10-15% SF at later ages suggests that an intermediate SF dosage provided a better balance between cement dilution, packing and secondary C-S-H formation. The subsequent reduction at 20% indicates that the beneficial mechanisms were insufficient to offset the higher replacement level under the tested mixture conditions.

4.2 Effect of RCA at 10% silica fume

RCA replacement	7-day (MPa)	14-day (MPa)	28-day (MPa)	28-day retention
0% (control)	20	30	38	100.0%
5% RCA	12	23.3	31.9	83.9%
10% RCA	13.1	23.5	30.8	81.1%
15% RCA	11	20.8	30.0	78.9%
20% RCA	11	20.4	29.0	76.3%

Table 5. Reported average compressive strength for mixes containing 10% SF and varying RCA.

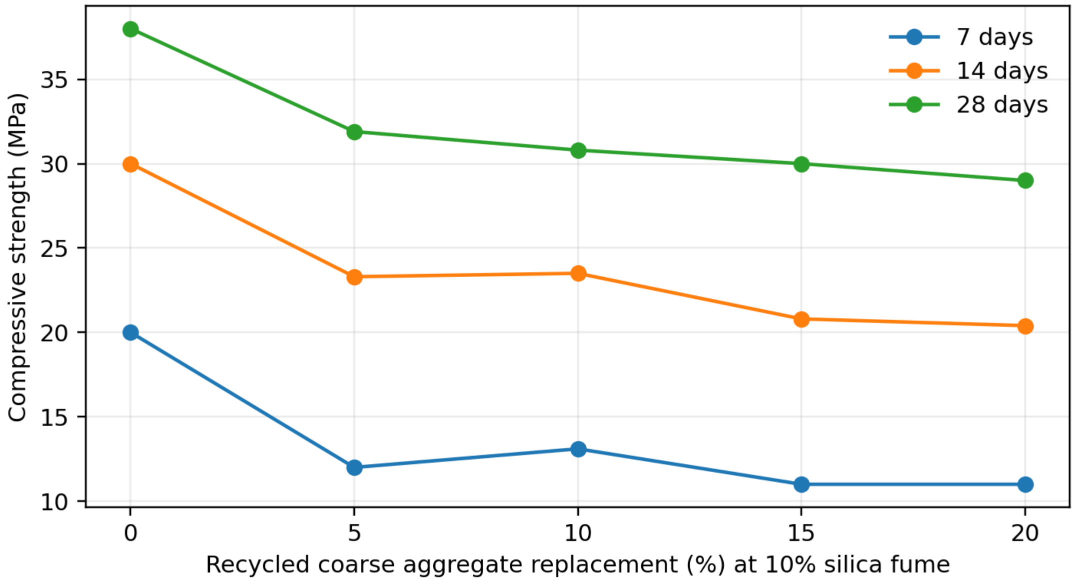

Figure 2. Strength development with RCA replacement at 10% silica fume.

For the combined SF-RCA series, the highest 28-day strength among recycled-aggregate mixtures was 31.9 MPa at 5% RCA. As RCA increased to 10, 15 and 20%, the 28-day strength decreased to 30.8, 30.0 and 29.0 MPa. The decline is approximately monotonic and is consistent with the recognized effects of residual mortar, greater porosity and additional interfacial transition zones in RCA [1,2,8].

The 10% SF addition does not fully restore the control strength, but the recycled mixes remain within a relatively narrow 29.0-31.9 MPa band at 28 days. This suggests that low-to-moderate recycled aggregate fractions may be practicable when the required design strength, durability class and variability are verified by statistically adequate trial batches.

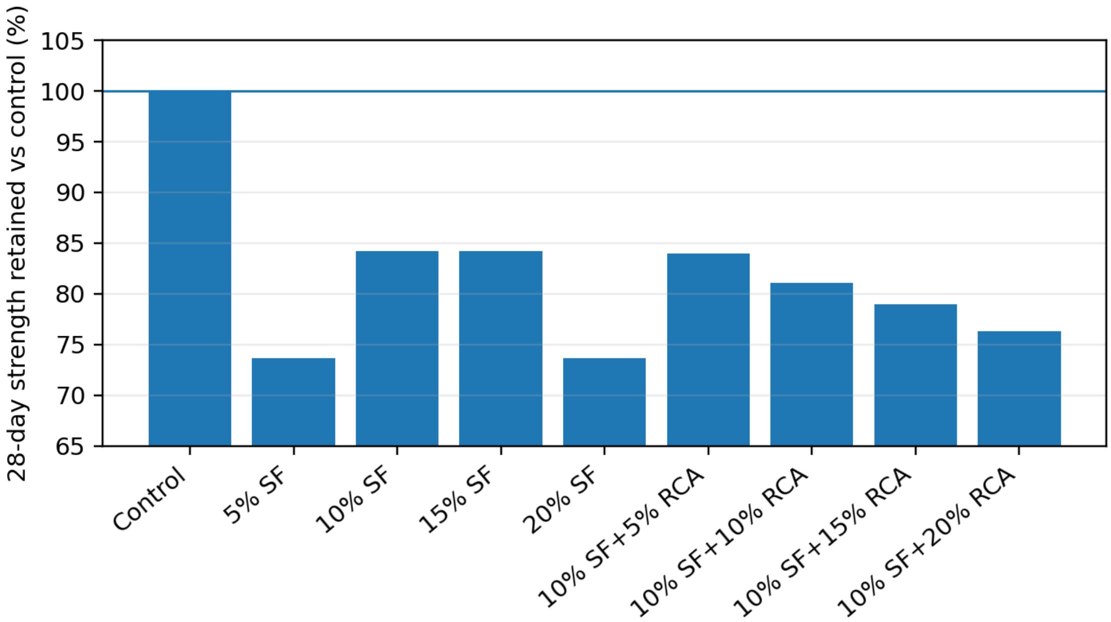

Figure 3. Recalculated 28-day strength retained relative to the reported 38 MPa control.

5. Discussion

5.1 Comparison with published literature

The observed reduction in strength with increasing RCA content agrees with the broad literature. Safiuddin et al. [1] and Wang et al. [2] describe how adhered mortar and its microcracking increase absorption and reduce stiffness and strength. Qasim et al. [7] similarly observed reductions in several mechanical indicators as recycled aggregate content increased, although the magnitude depends on the quality of recycled aggregate and mixture proportions. The current results therefore fit the expected qualitative response of untreated or conventionally processed RCA.

The SF series shows a non-monotonic response: 10 and 15% SF outperform 5 and 20% SF at 28 days. This is consistent with reviews finding an optimum dosage rather than indefinite improvement with increasing SF [3,4,10]. At moderate dosage, the filler effect and pozzolanic reaction can refine pore structure and strengthen the paste-aggregate interface. At excessive dosage, increased water demand, reduced workability, agglomeration and cement dilution may offset these gains if mixture water and admixture dosage are not optimized.

Habibi et al. [5] specifically studied recycled aggregate concrete containing silica fume and GGBFS and showed that optimization must consider more than a single variable. Their work supports the interpretation that the best sustainable mixture is a balance among strength, durability and environmental objectives rather than the mixture with the maximum waste replacement. Berndt [12] likewise demonstrated that supplementary cementitious materials can partly compensate for performance losses in concrete incorporating recycled aggregate.

5.2 Interpretation of strength-retention ratios

The project conclusion states that 10 and 15% SF 'retain strength up to 91%'. Direct calculation from the reported averages gives 32/38 = 0.842, or 84.2%. The combined mix with 10% SF and 5% RCA gives 31.9/38 = 83.9%. These recalculated values are used in Figure 3. This distinction is important because journal reporting should make all derived percentages reproducible from the primary table values.

Despite the lower strength relative to control, the dataset still identifies a technically meaningful pattern. The strength penalty from 5% to 20% RCA at fixed 10% SF is gradual rather than abrupt. This provides a basis for a future optimization programme in which RCA could be increased while adjusting pre-soaking, aggregate moisture correction, superplasticizer dosage, SF content and total binder content.

5.3 Sustainability significance

The environmental rationale for the combined system is twofold. First, replacing natural coarse aggregate with processed demolition concrete conserves virgin aggregate and creates a productive route for construction and demolition waste. Second, replacing part of Portland cement with SF uses an industrial by-product and can reduce clinker demand per unit volume of concrete. However, sustainability claims should account for transport distance, crushing energy, processing requirements, replacement efficiency, service life and durability. Recent life-cycle research cautions that recycled concrete does not automatically guarantee lower climate impact in every supply chain [11].

Accordingly, the present work should be viewed as a mechanical-performance screening study rather than a complete environmental assessment. Its strongest sustainability contribution is the identification of mixture ranges that warrant further testing: 10-15% SF in the cement-replacement series and relatively low RCA contents when 10% SF is used. Confirmation through durability and life-cycle metrics is required before assigning an optimum sustainable mixture.

5.4 Microstructural interpretation of the observed trends

Although microstructural testing was not part of the documented experimental programme, the observed strength trends can be interpreted using well-established mechanisms. RCA introduces at least two types of interfaces: the original aggregate-old mortar interface inherited from the parent concrete and the new mortar-RCA interface formed during recasting. The old mortar may contain pores and microcracks generated during service and crushing. Under compression, these heterogeneities can localize strain and initiate cracking earlier than in concrete containing dense virgin aggregate.

Silica fume can influence these interfaces through both particle packing and pozzolanic reaction. Very fine particles occupy spaces between larger cement grains and can reduce connected capillary porosity. As hydration proceeds, reactive silica consumes calcium hydroxide and forms additional C-S-H. This can strengthen the bulk paste and potentially improve the new interfacial transition zone around RCA. However, if SF content becomes too high without adequate water-reducing admixture or dispersion, loss of workability and local agglomeration may increase entrapped air and prevent full compaction. The lower 20% SF strength in the present data is therefore qualitatively plausible.

5.5 Engineering meaning of the reported strength level

The reported 28-day values of approximately 29-32 MPa for the modified mixtures should not be interpreted solely as a percentage loss from the 38 MPa control. In practice, suitability depends on the specified characteristic strength, exposure class, member type, quality-control margin and statistical variability. A modified mixture that is lower than a laboratory control may still be technically useful if it reliably satisfies the design requirement and demonstrates adequate durability. Conversely, a high average strength with large scatter or poor durability would not justify structural adoption.

For this reason, the next experimental phase should establish at least three independent batches per selected mixture, report mean strength with standard deviation and coefficient of variation, and compare characteristic strength using the applicable acceptance criteria. Workability should be recorded at a fixed time after mixing, and RCA should be tested in oven-dry, air-dry and saturated-surface-dry terms so that absorbed water is distinguished from effective mixing water. These additions would convert the present screening study into a stronger basis for mix qualification.

6. Practical Implications for Civil Engineering

- For non-critical and trial applications, low RCA replacement combined with a moderate SF dosage can be considered as a starting point for mix optimization, subject to compliance with the required characteristic strength and durability provisions.
- RCA moisture condition must be controlled because its absorption can change the effective water-binder ratio and workability; pre-soaking or moisture correction should be documented.
- Silica fume should be dispersed adequately and typically requires workability control; a consistent mixing sequence and compatible chemical admixture strategy are important in scaled production.
- Strength acceptance should be based on sufficient replicate specimens and statistical criteria rather than a single average. Reporting standard deviation and coefficient of variation would substantially improve confidence in future work.
- For structural applications, compressive strength alone is insufficient. Splitting tensile strength, modulus of elasticity, shrinkage, chloride penetration, carbonation, sorptivity and long-term performance should be tested before field adoption.

7. Limitations and Quality-Control Considerations

The main limitation is that the available project report provides compressive-strength data but does not supply a complete, internally consistent record of final mixture quantities, slump/workability for each mixture, RCA source strength, RCA grading, moisture conditioning, admixture dosage, specimen-to-specimen standard deviations or durability test results for the tested series. The grade designation is also inconsistent between different sections. These limitations prevent rigorous statistical inference and make it inappropriate to generalize a universal optimum percentage from this dataset alone.

The paper therefore reports the experimental observations conservatively. Before submission to a peer-reviewed journal, the authors should cross-check the manuscript against original batching sheets and compression-testing-machine records; confirm whether the mix was M30 or M35; verify the anomalous control 14-day entries; provide actual batch proportions in kg/m^3; and, if available, calculate standard deviation, coefficient of variation and significance tests from the raw replicate data.

8. Recommended Future Experimental Programme

A structured second-stage programme is recommended to convert the current findings into a publication-ready optimization study. The most efficient approach is to retain the

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control and concentrate testing around the better-performing SF range (for example 8-15%) while examining RCA at 0, 10, 20, 30 and 40%. A factorial or response-surface design could then quantify interactions between SF and RCA rather than studying them in separate one-factor series.

Investigation	Suggested response	Purpose
Fresh concrete	Slump, density, air content	Quantify workability and compaction changes caused by SF and RCA.
Mechanical	Compressive, split tensile, flexural, modulus	Establish whether strength trends extend beyond cube compression.
Transport/durability	Water absorption, sorptivity, RCPT/chloride migration, carbonation	Assess whether SF offsets RCA-related permeability and durability penalties.
Volume stability	Drying shrinkage and, if feasible, creep	Evaluate effects of porous old mortar and higher paste demand.
Microstructure	SEM/EDS, ITZ imaging, optional XRD/TGA	Verify densification and pozzolanic mechanisms.
Sustainability	Cement savings, virgin aggregate savings, transport and embodied CO2	Determine whether mechanical trade-offs produce a net environmental benefit.
Statistics	Replicate batches, SD, CoV, ANOVA/RSM	Quantify variability and significance of replacement effects.

Table 6. Proposed second-stage experimental plan for journal-quality validation.

A durability-based optimum may differ from a strength-based optimum. For example, an SF dosage that does not maximize compressive strength may still minimize chloride penetration or sorptivity. Similarly, a higher RCA content may be environmentally preferable if it remains within required strength and service-life limits. The final recommended mixture should therefore be selected using a multi-criteria framework rather than one response alone.

8. Conclusions

1. The control concrete had a reported average 28-day compressive strength of 38 MPa.

2. For silica fume as cement replacement, 10% and 15% SF each produced the highest 28-day strength among the replacement mixes, 32 MPa. This equals 84.2% of the reported control strength. The 5% and 20% SF mixtures each recorded 28 MPa at 28 days.

3. With silica fume fixed at 10%, increasing RCA from 5 to 20% progressively reduced the reported 28-day strength from 31.9 to 29.0 MPa. The corresponding strength retention relative to control decreased from 83.9 to 76.3%.

4. The observed trends are compatible with established mechanisms in the literature: RCA introduces porous adhered mortar and additional interfacial zones, while properly dosed SF can refine pores and generate additional C-S-H through pozzolanic reaction.

5. Within the tested dataset, moderate SF replacement and low RCA replacement are the most promising combinations for further optimization. A definitive structural recommendation requires verification of the concrete grade, complete mix proportions, statistical replication and durability performance.

6. Future research should extend the study to tensile/flexural strength, elastic modulus, sorptivity, chloride penetration, carbonation, shrinkage, microstructure (SEM/EDS), embodied-carbon or life-cycle assessment, and larger RCA replacement ranges with moisture-conditioning protocols.

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