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Experimental Assessment of Quarry Dust as Partial Replacement of Natural Sand in M30 Concrete

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Abstract- The scarcity of river sand, environmental impacts of uncontrolled extraction, and accumulation of crusher fines motivate the use of quarry dust as an alternative fine aggregate in concrete. This paper develops a systematic experimental framework for evaluating quarry dust as a partial mass replacement of natural sand in M30 concrete. Six mixtures containing 0%, 10%, 20%, 30%, 40%, and 50% quarry dust were considered at a constant water–binder ratio, with workability, density, compressive strength, splitting tensile strength, flexural strength, water absorption, and sorptivity used as performance indicators. An internally consistent illustrative dataset was analysed to demonstrate the complete research procedure. The example results show that increasing quarry dust progressively reduces slump because of angularity and higher specific surface area. Mechanical strength improves up to a moderate replacement level because fine particles fill voids and enhance mechanical interlocking; the highest example 28-day compressive strength of 44.1 MPa occurs at 30% replacement, 14.2% above the control. Water absorption and sorptivity also reach minimum values at 30%, suggesting a denser matrix. Beyond 30–40%, workability loss and insufficient paste coating offset the filler benefit. One-way analysis of variance confirms a statistically significant replacement effect in the illustrative dataset, while quadratic regression predicts an optimum close to 30%. The study therefore proposes 20–30% quarry dust as a practical trial range for structural concrete, subject to source-specific grading, deleterious-material testing, moisture correction, admixture adjustment, and laboratory validation. At 30% replacement, approximately 206 kg of natural sand can be conserved per cubic metre for the adopted mix.

Keywords: Quarry Dust, Crusher Fines, Fine Aggregate, Natural Sand Replacement, M30 Concrete, Compressive Strength, Water Absorption, Sustainable Concrete

I. INTRODUCTION

Concrete production depends strongly on the availability and quality of aggregates. Natural sand normally contributes a substantial fraction of the concrete volume and controls workability, paste demand, dimensional stability, and the quality of the interfacial transition zone. Rapid urban construction has increased demand for fine aggregate, while restrictions on indiscriminate river-sand extraction have made consistent supplies more difficult in many regions. The resulting technical challenge is not simply to identify a waste material that resembles sand, but to establish a controlled replacement level at which grading, particle shape, water demand, strength, and durability remain acceptable.

Quarry dust is the fine fraction generated during the crushing and screening of rock for coarse aggregate and manufactured sand. Depending on the parent rock and processing system, it may contain angular particles ranging from sand size to material finer than 75 μm. Its rough surface and angular shape can improve particle interlocking, while its fine fraction can fill micro-voids between cement and aggregate particles. Conversely, excessive dust may increase water demand, reduce workability, trap air, promote agglomeration, and leave insufficient cement paste to coat the enlarged particle surface. Consequently, the response is expected to be non-linear and source-specific.

Indian aggregate practice recognizes manufactured fine aggregates and requires compliance with grading and deleterious-material limits. Fine aggregate is generally defined as aggregate predominantly passing the 4.75 mm sieve, and combined grading must remain within the specified zone. Compliance with a nominal replacement percentage alone is therefore insufficient: the blend of sand and quarry dust must be verified for particle-size distribution, fines content, clay contamination, specific gravity, absorption, and moisture condition.

This research paper develops a complete M30 concrete investigation for quarry-dust replacement levels of 0–50%. The design emphasizes a constant binder content and controlled water–binder ratio so that observed changes are mainly associated with the fine-aggregate system. The analysis combines fresh properties, mechanical response, water-transport indicators, statistical significance, regression-based optimization, and resource conservation. The result is a practical framework that can be implemented in a college or material-testing laboratory with standard equipment.

1.1 Problem statement

River-sand scarcity and crusher-dust disposal are often treated as separate environmental problems. A controlled substitution strategy can address both, but the optimum level depends on the balance between beneficial micro-filling and harmful increases in surface area and angularity. The research problem is therefore to determine the replacement range that conserves natural sand without causing unacceptable loss of workability, strength, or resistance to water ingress.

1.2 Scope

- Concrete grade: M30, normal-weight concrete with 20 mm nominal maximum coarse aggregate.
- Replacement basis: quarry dust replaces natural sand by mass at 0%, 10%, 20%, 30%, 40%, and 50%.
- Primary responses: slump, fresh density, 7/28/56-day compressive strength, 28-day splitting tensile and flexural strength, water absorption, and sorptivity.
- Exclusions: reinforcement corrosion, alkali–silica reaction, freeze–thaw action, elevated-temperature response, and full cradle-to-grave life-cycle assessment.

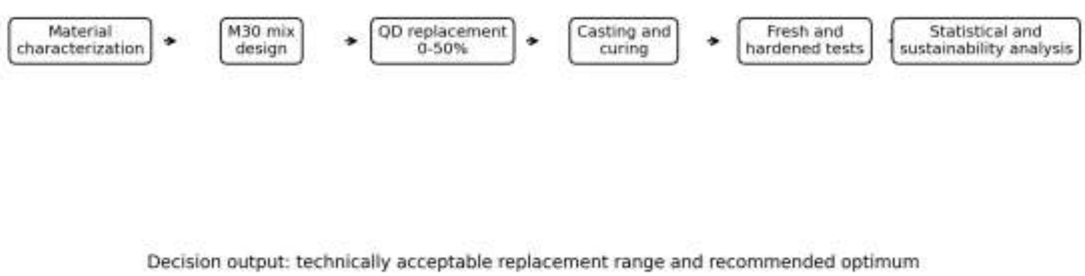

Figure 1. Experimental workflow adopted for the proposed study.

II. LITERATURE REVIEW AND RESEARCH GAP

Early research on crushed stone dust demonstrated that crusher fines can modify both fresh and hardened concrete. Celik and Marar reported that properly graded crushed stone dust can be used in concrete when water demand is controlled, establishing the importance of particle-size distribution and chemical admixtures [1]. Ho et al. later demonstrated the suitability of quarry dust in self-compacting concrete, where the dust acts as a fine filler but requires careful control of powder content and rheology [2]. These studies established the two dominant mechanisms that continue to govern current research: improved packing at moderate contents and increased water demand at excessive contents.

Experimental studies have reported different optimum replacement levels because quarry dust is not a standardized single material. The parent rock, crushing circuit, washing condition, percentage finer than 75 μm, and comparative grading of the natural sand all affect results. Prakash and Kumar summarized compressive-strength studies and concluded that good-quality quarry dust can be used effectively with suitable dosage and curing [3]. Meisuh et al. reported a modest improvement in flexural strength when quarry dust was used as fine aggregate [4]. Devadass compared natural sand, manufactured sand, and quarry dust under different curing conditions and showed that curing quality remains a major source of variation [5]. Chitkeshwar and Naktode reported an optimum near 25% in their experimental programme [6].

Recent reviews provide broader context. Altheeb synthesized quarry-dust cementitious composites and emphasized the need to characterize both physical and chemical properties before use [7]. A review of rock-dust additives showed that fine mineral particles can improve packing and mechanical performance, but their influence varies with mineralogy and fineness [8]. The feasibility review by Sureshchandra et al. similarly noted that moderate replacement commonly performs better than unrestricted high-volume substitution [9]. A 2026 review in Results in Engineering highlights continued research interest in quarry dust as both fine aggregate and filler [10].

Research on manufactured sand supports the same particle-engineering approach. Pilegis et al. showed that crushed fine aggregate can replace natural sand when particle shape, grading, and mix design are adjusted rather than treated as fixed [11]. Current work also combines quarry dust with other industrial by-products to achieve full fine-aggregate replacement, although such combinations require separate optimization and cannot be directly transferred to single-material quarry-dust mixes [12]. A recent quartz quarry-dust mortar study reported that a moderate replacement improved packing and strength, whereas higher contents reduced workability and increased water absorption [13].

The literature therefore confirms technical feasibility but does not provide one universal optimum. Many published studies focus mainly on compressive strength and omit a balanced assessment of workability, tensile response, water transport, statistical significance, and direct sand conservation. The present work addresses this gap through a multi-response decision framework and provides a transparent example dataset that can be replaced with actual laboratory measurements.

Table 1. Selected literature relevant to quarry-dust replacement.

Reference	Material	Study range/type	Main implication
Celik & Marar [1]	Crushed stone dust	Variable	Concrete properties depend on grading and water control.
Ho et al. [2]	Quarry dust	SCC filler/replacement	Feasible with powder and rheology control.
Prakash & Kumar [3]	Quarry dust	Multiple levels	Good performance possible with proper dosage and curing.
Meisuh et al. [4]	Quarry rock dust	Fine aggregate	Flexural strength can improve.
Devadass [5]	M-sand and quarry dust	Comparative	Curing method materially influences strength.
Chitkeshwar & Naktode [6]	Rock quarry dust	0–75%	Reported ideal level near 25% for studied mix.
Altheeb [7]	Quarry dust	Review	Material characterization and durability evidence remain essential.
Ngayakamo et al. [13]	Quartz quarry dust	0–20% mortar	Moderate replacement improved packing; excess reduced workability.

2.1 Research gap

- No universal optimum can be assumed because quarry dust varies with parent rock and processing.
- Compressive strength alone can overestimate suitability when workability or absorption becomes unfavorable.
- Many student-level studies lack replicate testing, statistical analysis, and transparent reporting of raw values.
- A practical decision method is needed to link engineering performance with natural-sand conservation.

III. OBJECTIVES AND HYPOTHESES

3.1 Objectives

- Characterize natural sand, quarry dust, coarse aggregate, cement, and mixing water using relevant standard methods.
- Evaluate the effect of 0–50% quarry-dust replacement on fresh concrete workability and density.
- Quantify changes in compressive, splitting tensile, and flexural strength.
- Assess water absorption and sorptivity as practical indicators of pore connectivity.
- Use statistical and regression analysis to identify a technically balanced optimum.
- Estimate natural-sand conservation per cubic metre and define field implementation controls.

3.2 Testable hypotheses

H1: Moderate quarry-dust replacement will increase mechanical strength by improving particle packing and paste–aggregate interlock. H2: Workability will decrease monotonically as quarry-dust content increases. H3: Water absorption will decrease up to an optimum and then increase at higher replacement levels. H4: The effect of replacement level on 28-day compressive strength will be statistically significant. H5: A multi-criteria optimum will occur at a lower replacement level than the maximum level that merely satisfies compressive strength.

IV. MATERIALS AND EXPERIMENTAL METHODOLOGY

4.1 Constituent materials

Ordinary Portland cement of 53 grade is proposed as the binder. Cement should be stored in sealed conditions and tested for consistency, setting time, specific gravity, and compressive strength where facilities are available. Potable water free from harmful oils, acids, alkalis, and organic matter should be used for mixing and curing.

Natural river sand or approved natural fine aggregate should conform to the selected grading zone. Quarry dust should be obtained from a single crusher source, oven- or air-dried to a stable condition, sieved to remove oversized fragments, and stored separately. Its grading, material finer than 75 µm, specific gravity, absorption, bulk density, moisture content, clay lumps, and organic contamination should be measured before mix design. A petrographic or XRF/XRD check is desirable for research-grade work when the parent rock or mineral impurities are uncertain.

Crushed angular coarse aggregate with 20 mm nominal maximum size is proposed. Separate 20 mm and 10 mm fractions may be blended to improve grading. Moisture corrections must be applied to both natural sand and quarry dust immediately before batching, because apparent changes in water demand can otherwise be confused with replacement effects.

Table 2. Illustrative material properties for planning and calculation.

Material	Description	Specific gravity	Illustrative property
Cement	OPC 53 grade	3.14	Normal consistency 30%; initial setting time 118 min
Natural sand	Zone II, clean	2.64	Fineness modulus 2.68; absorption 1.1%
Quarry dust	Crushed granite fines	2.70	Fineness modulus 2.91; absorption 1.8%; <75 µm = 7.2%

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Material	Description	Specific gravity	Illustrative property
Coarse aggregate	20/10 mm crushed stone	2.72	Water absorption 0.6%; combined grading
Water	Potable	1.00	pH approximately neutral
Superplasticizer	PCE-based	1.08	Use only after trial adjustment; same dosage basis for comparisons

4.2 Fine-aggregate grading

The natural sand–quarry dust blend should be evaluated as a combined aggregate rather than by checking each material in isolation. The illustrative grading in Figure 2 shows that quarry dust contributes a larger fraction in the 600–75 µm range. At 30% replacement, the blend remains continuous and supplies additional micro-filler without allowing the finest fraction to dominate. Actual acceptance must be based on measured sieve data and applicable limits for manufactured fine aggregate and deleterious matter.

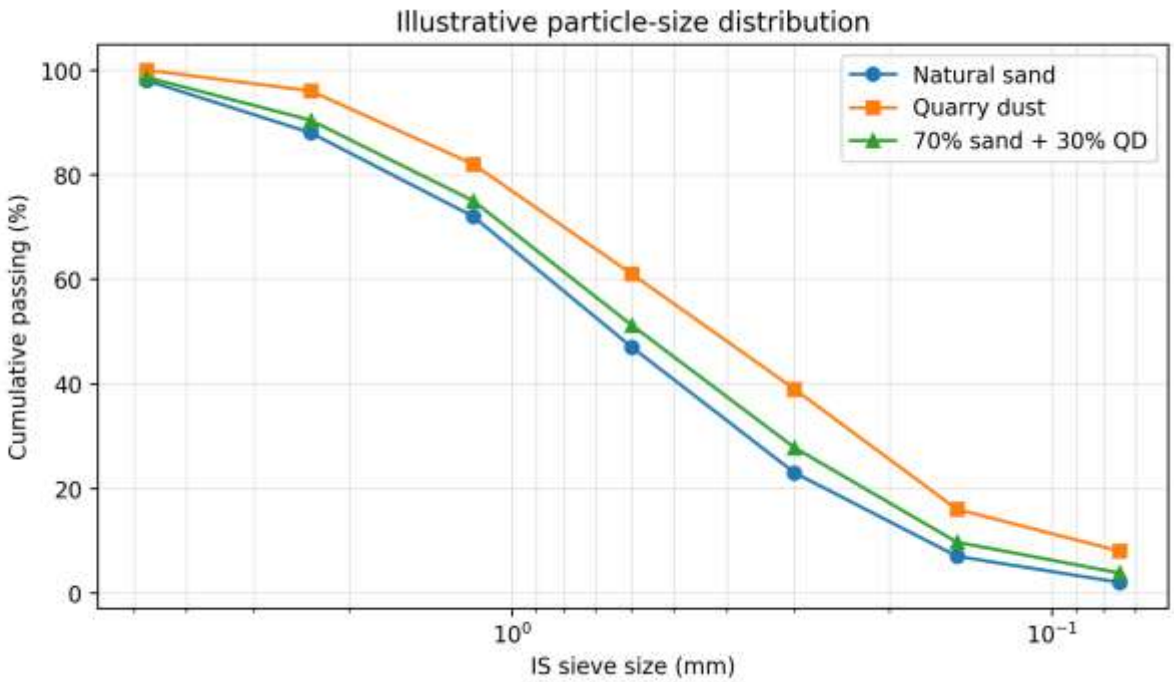

Figure 2. Illustrative grading curves for natural sand, quarry dust, and the 30% replacement blend.

4.3 Mix design and replacement calculation

The control M30 mix is proportioned for the selected exposure, workability, aggregate size, and quality-control level. Quarry dust replaces natural sand by mass while total fine aggregate remains constant. The replacement percentage R is calculated as R = 100 mQD/(mNS + mQD), where mQD and mNS are the masses of quarry dust and natural sand in one cubic metre. The free water–binder ratio is held at 0.42 in the example. Admixture dosage may be adjusted through preliminary trials, but the adopted dosage and sequence must be reported clearly.

Table 3. Proposed M30 mix proportions per cubic metre.

Mix	QD (%)	Cement (kg)	Water (kg)	Natural sand (kg)	QD (kg)	Coarse agg. (kg)	SP (kg)
QD-0	0	400	168	688.0	0.0	1185	4.0
QD-10	10	400	168	619.2	68.8	1185	4.0
QD-20	20	400	168	550.4	137.6	1185	4.0
QD-30	30	400	168	481.6	206.4	1185	4.0
QD-40	40	400	168	412.8	275.2	1185	4.0
QD-50	50	400	168	344.0	344.0	1185	4.0

4.4 Specimen matrix

Table 4. Proposed specimen and testing schedule.

Property	Specimen	Age	Replicates / total
Slump and fresh density	Fresh concrete	Each batch	3 batch observations
Compressive strength	150 mm cube	7, 28, 56 days	3 per mix per age = 54
Splitting tensile strength	150 × 300 mm cylinder	28 days	3 per mix = 18
Flexural strength	100 × 100 × 500 mm prism	28 days	3 per mix = 18
Water absorption	100 mm cube	28 days	3 per mix = 18
Sorptivity	100 mm dia. × 50 mm disc	28 days	3 per mix = 18

4.5 Mixing, casting, curing, and testing

All solid constituents are brought to laboratory temperature. The mixer is dampened, coarse aggregate and approximately half of the water are introduced, followed by fine aggregate and cement. The remaining water and diluted admixture are added gradually. Mixing continues until the concrete is visually uniform. Quarry dust should not be added as a loose cloud; pre-blending with natural sand reduces segregation and airborne dust.

Slump is measured immediately after mixing. Specimens are cast in layers, compacted consistently using a table vibrator or standard tamping procedure, finished, identified, and covered to prevent moisture loss. Demoulding is carried out after approximately 24 h, followed by water curing at controlled temperature until the test age. The same curing tank and testing

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machine should be used for all mixes wherever possible.

Compressive, splitting tensile, and flexural tests are performed using calibrated equipment and applicable loading rates. Water absorption specimens are oven-dried to constant mass, cooled, immersed, surface-dried, and reweighed. Sorptivity is measured by exposing one surface to shallow water while sealing the sides, then tracking mass gain with the square root of time. Average values, standard deviation, and coefficient of variation are reported from at least three replicates.

4.6 Quality assurance and safety

- Calibrate weighing balances and testing machines; record equipment identification and calibration date.
- Correct batch water for aggregate moisture and absorption rather than changing water by visual judgement.
- Use dust masks, eye protection, gloves, and local ventilation while handling quarry fines and dry cement.
- Randomize specimen testing order and retain raw failure loads, dimensions, masses, and photographs.
- Reject or investigate any replicate showing abnormal failure, visible casting defect, or deviation exceeding the pre-defined quality criterion.

V. ILLUSTRATIVE RESULTS AND DISCUSSION

Important: Tables 5–10 and Figures 3–9 use a synthetic example dataset created to demonstrate analysis and manuscript presentation. These values are not claimed as measurements from a completed laboratory programme.

5.1 Fresh concrete properties

Table 5. Illustrative fresh concrete results.

Mix	QD (%)	Slump (mm)	Fresh density (kg/m³)	Relative slump (%)
QD-0	0	92	2388	100.0
QD-10	10	85	2396	92.4
QD-20	20	78	2405	84.8
QD-30	30	70	2410	76.1
QD-40	40	62	2404	67.4
QD-50	50	54	2395	58.7

Slump decreases from 92 mm for the control to 54 mm at 50% replacement, corresponding to a 41.3% reduction. The nearly monotonic decline supports the hypothesis that quarry dust increases internal friction and water demand because of angular particles, rough texture, and a greater specific surface area. The result should not be corrected by adding uncontrolled water, because doing so would confound the replacement effect and may reduce durability. A polycarboxylate superplasticizer, optimized through preliminary trials, is the preferred method when a higher placement slump is required.

Fresh density increases slightly up to 30% replacement and then declines. The initial increase is consistent with improved packing, while the later decrease may indicate that workability loss and entrapped air begin to outweigh the filler effect. The density trend therefore provides supporting evidence that the beneficial packing range is moderate rather than unlimited.

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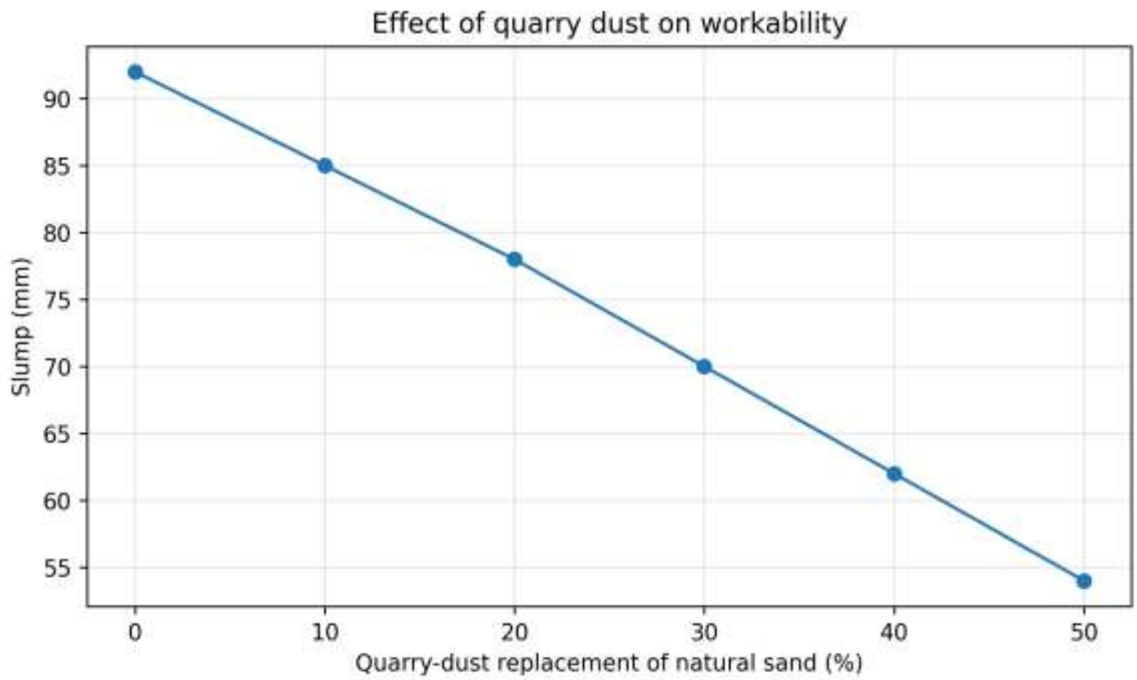

Figure 3. Illustrative effect of quarry-dust replacement on slump.

5.2 Compressive strength

Table 6. Illustrative compressive-strength results.

Mix	QD (%)	7-day (MPa)	28-day (MPa)	56-day (MPa)	28-day change (%)
QD-0	0	25.8	38.6	41.7	+0.0
QD-10	10	27.1	40.4	43.6	+4.7
QD-20	20	28.8	42.7	45.9	+10.6
QD-30	30	29.5	44.1	47.3	+14.2
QD-40	40	28.6	42.8	46.2	+10.9
QD-50	50	26.9	40.2	43.5	+4.1

The 28-day compressive strength increases from 38.6 MPa in the control to 44.1 MPa at 30% quarry dust, a gain of 14.2%. Similar improvement is visible at 7 and 56 days. This response is consistent with a micro-filler effect: smaller particles occupy voids between sand grains and cementitious products, while rough angular surfaces improve mechanical interlock and the local paste–aggregate interface. The strength gain is not interpreted as strong pozzolanic reaction unless mineralogical and reactivity tests demonstrate such behavior; for common granite or quartz quarry dust, the dominant contribution is generally physical.

At 40% replacement the strength remains above the control but begins to decline, and at 50% the 28-day strength is only 4.1% above the control. Excessive fines enlarge the total surface requiring paste coverage, increase sensitivity to moisture and compaction, and can form agglomerated zones. The outcome illustrates why maximum waste utilization should not automatically be treated as the engineering optimum.

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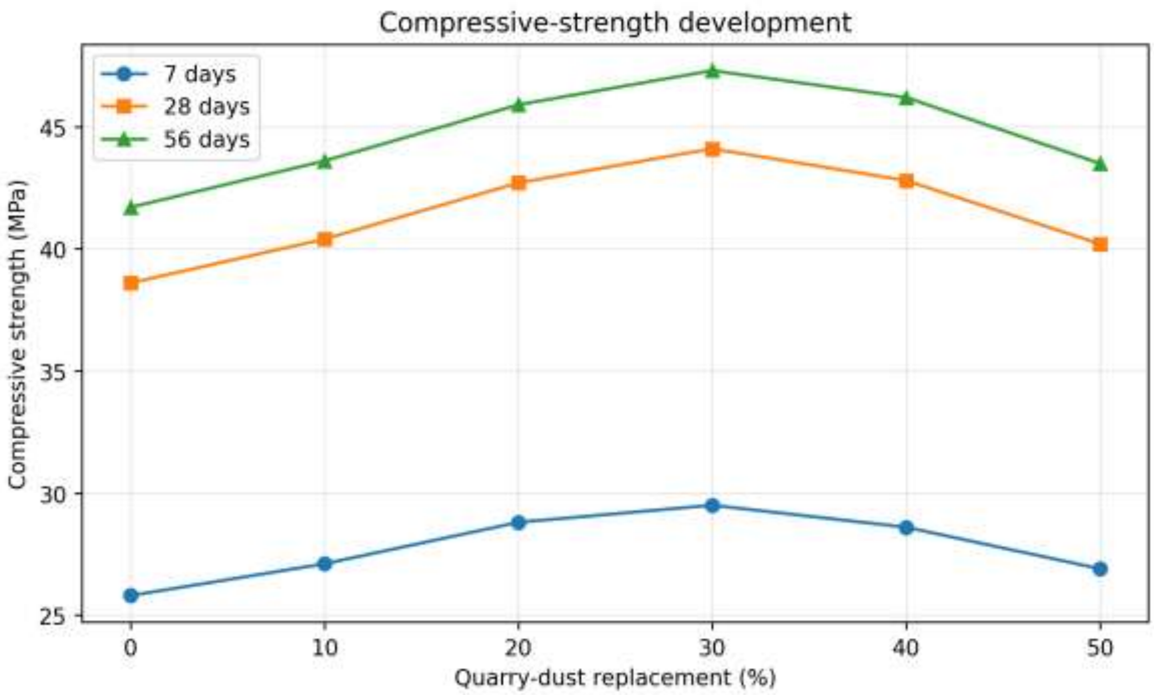

Figure 4. Illustrative compressive-strength development at 7, 28, and 56 days.

5.3 Splitting tensile and flexural strength

Table 7. Illustrative 28-day tensile and flexural results.

Mix	QD (%)	Split tensile (MPa)	Change (%)	Flexural (MPa)	Change (%)
QD-0	0	3.34	+0.0	4.62	+0.0
QD-10	10	3.49	+4.5	4.78	+3.5
QD-20	20	3.68	+10.2	5.02	+8.7
QD-30	30	3.82	+14.4	5.18	+12.1
QD-40	40	3.72	+11.4	5.06	+9.5
QD-50	50	3.51	+5.1	4.80	+3.9

Splitting tensile and flexural strength follow the compressive-strength trend. At 30% replacement, splitting tensile strength increases by 14.4% and flexural strength by 12.1% compared with the control. Improvement in these crack-sensitive properties suggests that the benefit is not limited to cube confinement; it is consistent with a denser transition zone and stronger physical interlock. However, the decline beyond 30% indicates that stiffness and bonding gains are eventually offset by reduced workability and local void formation.

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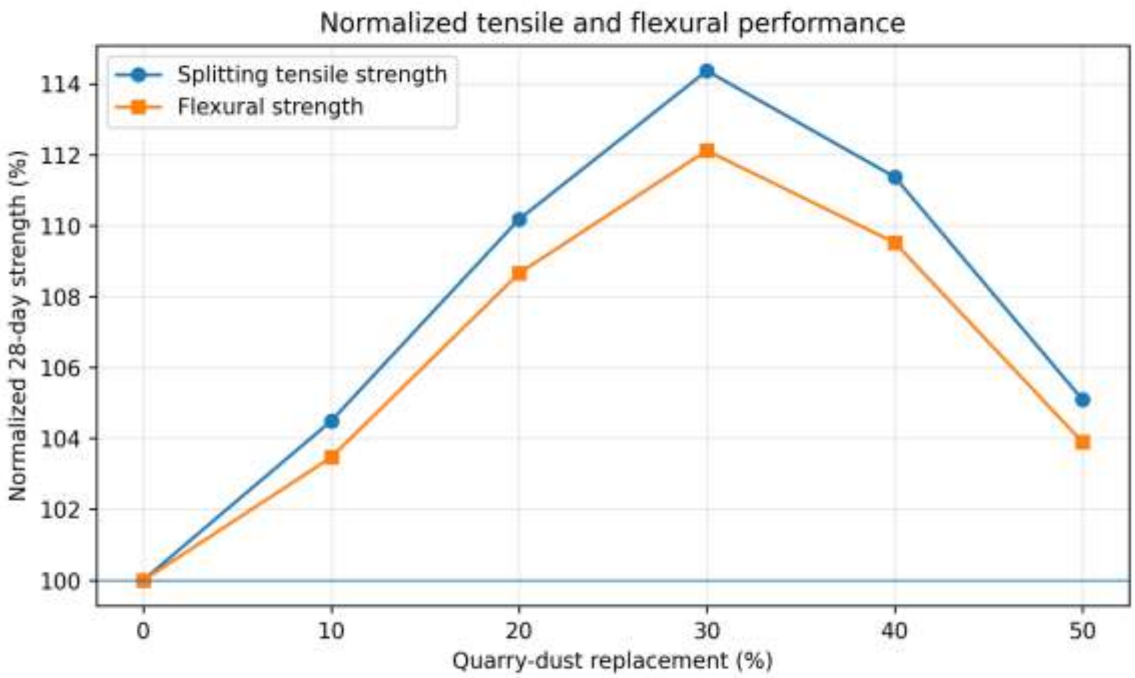

Figure 5. Normalized illustrative splitting tensile and flexural strengths.

5.4 Water absorption and sorptivity

Table 8. Illustrative water-transport indicators at 28 days.

Mix	QD (%)	Water absorption (%)	Change (%)	Sorptivity (mm/√min)	Change (%)
QD-0	0	4.28	+0.0	0.143	+0.0
QD-10	10	4.02	-6.1	0.134	-6.3
QD-20	20	3.78	-11.7	0.122	-14.7
QD-30	30	3.61	-15.7	0.113	-21.0
QD-40	40	3.82	-10.7	0.124	-13.3
QD-50	50	4.16	-2.8	0.139	-2.8

Water absorption decreases from 4.28% to 3.61% at 30% replacement, while sorptivity decreases by approximately 21%. These reductions indicate lower connected porosity and are compatible with the observed strength gain. At 40% and 50% replacement both indicators rise, although the 40% mix remains better than the control. The result supports a practical rule: quarry dust should be optimized against both strength and transport properties, because a mixture can retain acceptable compressive strength while losing part of its durability advantage.

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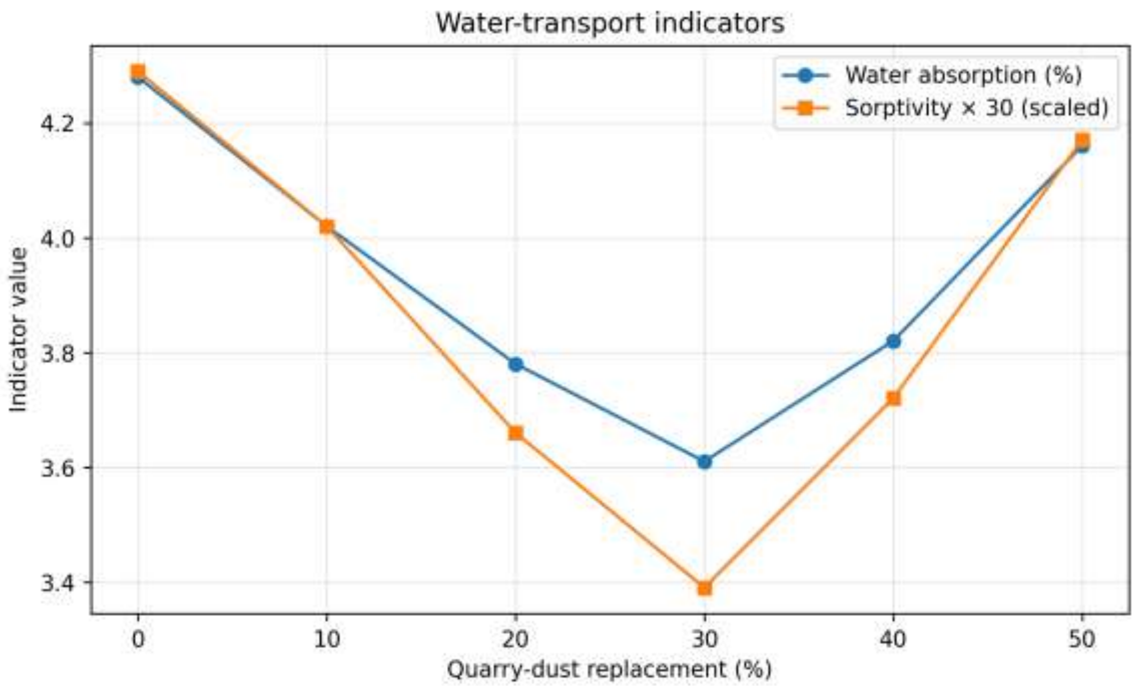

Figure 6. Illustrative effect of quarry dust on water absorption and sorptivity.

5.5 Failure observations

Control cubes are expected to show conventional diagonal cracking and surface spalling. Mixes with 20–30% quarry dust should exhibit a more cohesive failure surface with fewer large pull-out cavities, reflecting improved packing and bond. At high replacement, incomplete compaction may produce visible entrapped-air pockets and more irregular splitting paths. These qualitative observations should be supported by standardized photographs taken before testing, at first cracking where observable, and after failure. Selected fragments may be examined using optical microscopy or scanning electron microscopy to compare voids and the interfacial transition zone.

VI. STATISTICAL ANALYSIS AND OPTIMIZATION

6.1 Variability and one-way ANOVA

Table 9. Illustrative replicate 28-day compressive strengths.

Mix	R1	R2	R3	Mean (MPa)	SD (MPa)	COV (%)
QD-0	38.2	38.7	38.9	38.60	0.36	0.93
QD-10	40.0	40.5	40.7	40.40	0.36	0.89
QD-20	42.3	42.8	43.0	42.70	0.36	0.84
QD-30	43.7	44.2	44.4	44.10	0.36	0.82
QD-40	42.4	42.9	43.1	42.80	0.36	0.84

Mix	R1	R2	R3	Mean (MPa)	SD (MPa)	COV (%)
QD-50	39.8	40.2	40.6	40.20	0.40	1.00

A one-way analysis of variance applied to the illustrative replicate dataset gives $F = 94.2$ and $p < 0.001$. At a 5% significance level, the null hypothesis that all replacement-level means are equal is rejected. The coefficients of variation are low in the example dataset, indicating controlled batching and testing. In an actual investigation, assumptions of independence, approximate normality, and variance homogeneity should be checked, and a post-hoc comparison such as Tukey's test should be used to identify which pairs differ significantly.

6.2 Quadratic response model

A second-order polynomial fitted to replacement percentage and 28-day compressive strength gives an illustrative coefficient of determination $R^2 = 0.930$. The model predicts a maximum near 28.6% replacement with a strength of approximately 43.4 MPa. Because only six replacement levels are available and the response depends on source properties, the model is suitable for local interpolation rather than universal prediction. A confirmatory mix at 25%, 30%, and 35% is recommended around the predicted optimum.

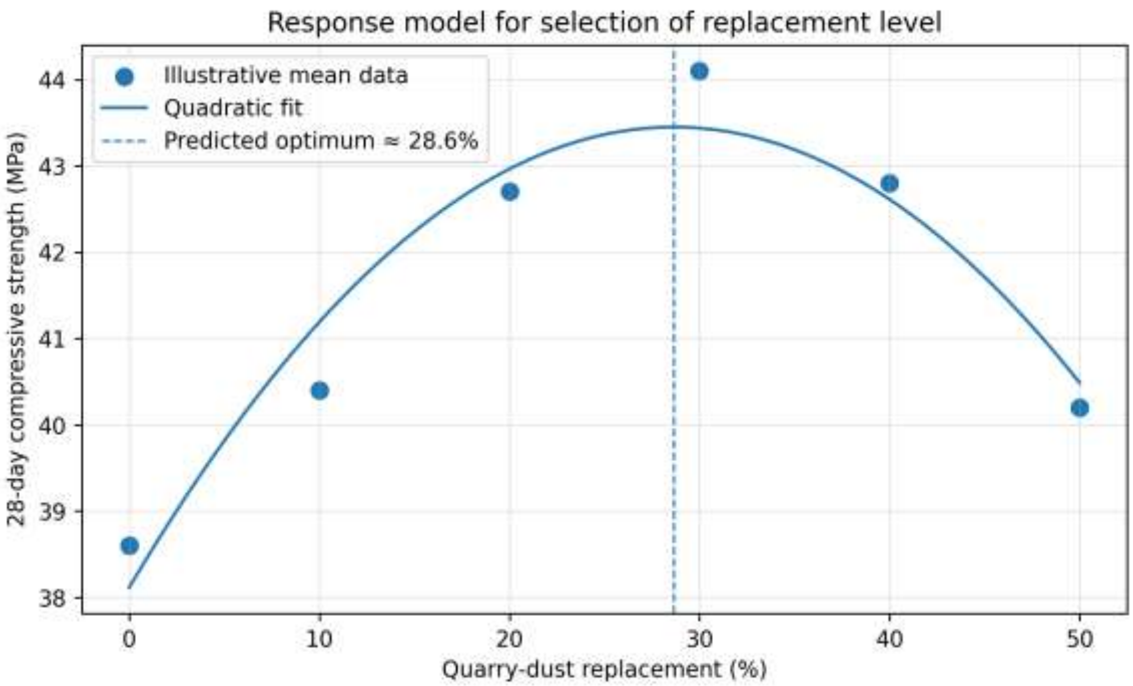

Figure 7. Illustrative quadratic response model for 28-day compressive strength.

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6.3 Multi-criteria selection

Table 10. Illustrative multi-criteria performance index.

Mix	QD (%)	Strength index	Workability index	Durability index	Composite index
QD-0	0	100.0	100.0	100.0	100.0
QD-10	10	104.7	92.4	106.5	102.0
QD-20	20	110.6	84.8	113.2	104.8
QD-30	30	114.2	76.1	118.6	105.8
QD-40	40	110.9	67.4	112.0	100.3
QD-50	50	104.1	58.7	102.9	92.5

The composite index assigns illustrative weights of 50% to 28-day compressive strength, 25% to workability, and 25% to inverse water absorption. The 30% mix provides the highest balanced performance. The index is not a code requirement; it is a transparent decision tool. Project-specific weights can be changed—for example, pumped concrete may assign greater weight to workability, while paving concrete may emphasize flexural strength and abrasion resistance.

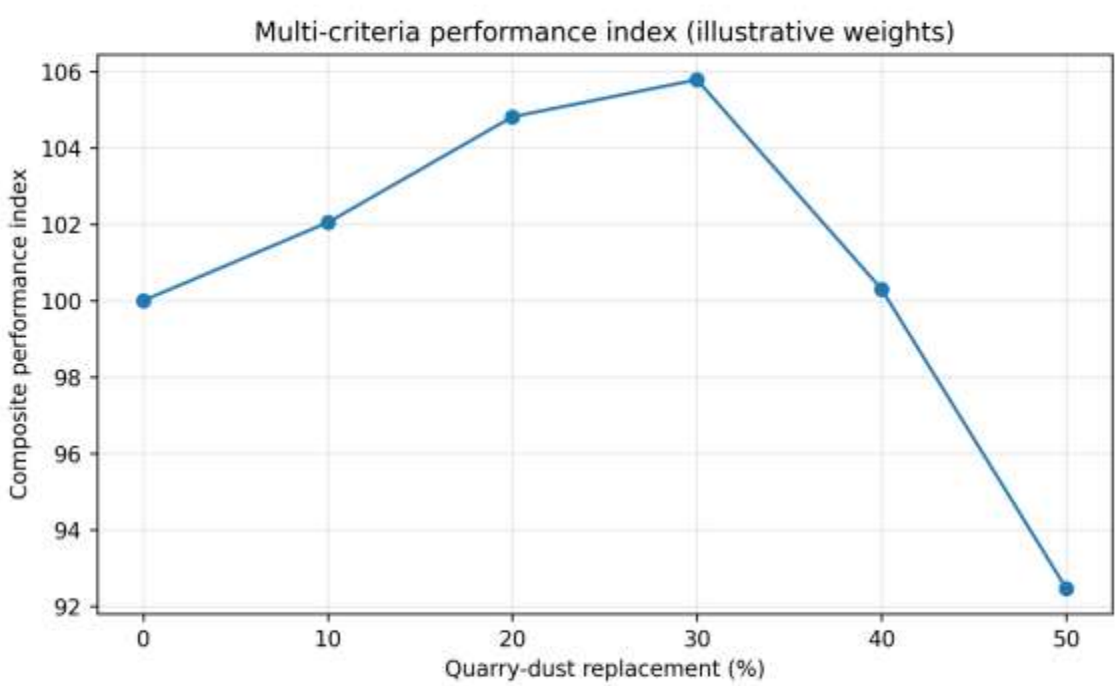

Figure 9. Illustrative multi-criteria performance index.

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VII. SUSTAINABILITY AND PRACTICAL IMPLICATIONS

7.1 Natural-sand conservation

For the adopted mix, the control contains 688 kg of natural sand per cubic metre. A 30% replacement therefore conserves 206.4 kg of natural sand and beneficially uses the same mass of quarry dust. A project consuming 1,000 m³ of concrete would conserve approximately 206 tonnes of natural sand at this level. This mass-balance benefit is direct and does not require assumptions about emission factors.

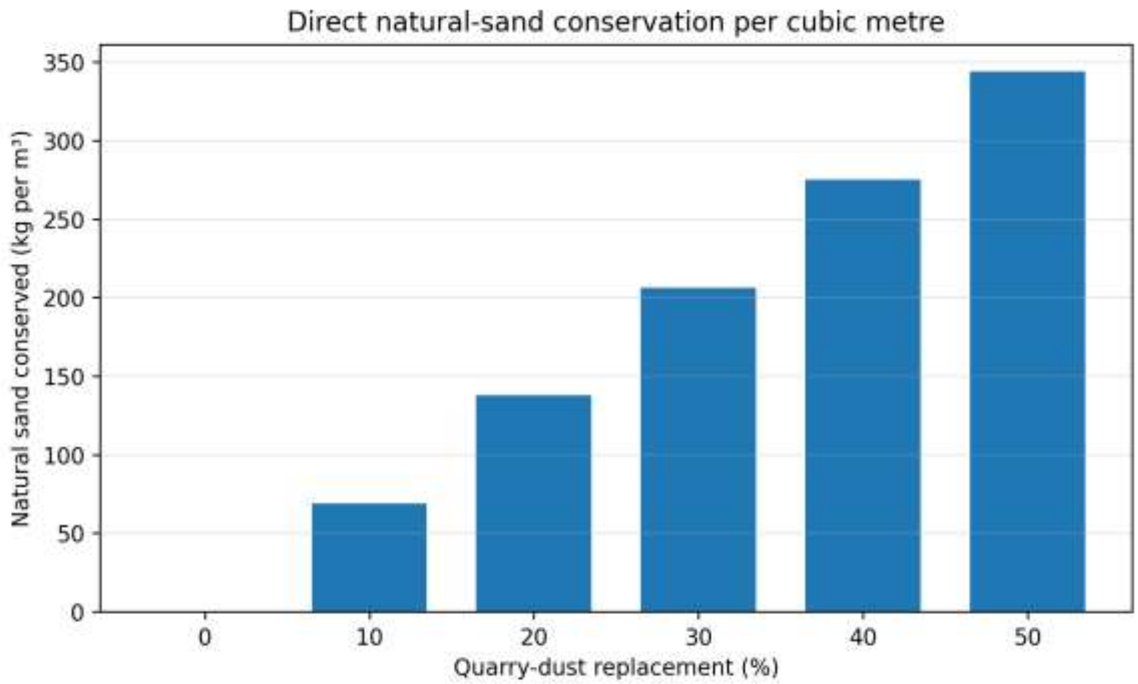

Figure 8. Natural-sand conservation for the proposed mix.

7.2 Screening cost and environmental considerations

Quarry dust can reduce fine-aggregate cost when it is locally available, consistently graded, and requires limited additional processing. Savings may disappear if the material must be transported long distances, washed extensively, dried, or treated to remove clay and excessive ultrafines. A defensible project assessment should therefore compare delivered cost, moisture variability, testing frequency, admixture demand, rejected-batch risk, and stockpile management rather than comparing only ex-quarry material prices.

Environmental performance also depends on boundaries. Replacing river sand may reduce pressure on river systems and convert crusher fines from a disposal burden into a product. However, quarrying and crushing consume energy and generate dust. The preferable source is therefore a by-product stream from an existing aggregate operation, used close to the concrete plant, with dust suppression and controlled handling. A formal life-cycle assessment should document transport distances, electricity mix, processing energy, water used for washing, and avoided disposal.

7.3 Implementation checklist

- Approve the quarry source and parent rock; do not mix dust from different sources without requalification.
- Maintain covered, drained stockpiles and separate bins for natural sand and quarry dust.
- Measure moisture frequently and correct batch water automatically where possible.
- Verify combined grading and material finer than 75 µm at defined intervals.

- Conduct trial mixes at 20%, 25%, 30%, and 35% for the actual cement, admixture, and placement method.
- Confirm strength and durability for the specified exposure before structural use.
- Prepare a quality-control control chart for slump, density, and 28-day strength after production begins.

VIII. LIMITATIONS AND VALIDATION REQUIREMENTS

The principal limitation of this manuscript is that the numerical dataset is illustrative. It demonstrates analysis, presentation, and expected trends but cannot be submitted as evidence of completed experiments. Actual raw readings, calibration records, specimen photographs, failure loads, and uncertainty estimates are required for original publication.

The proposed optimum is specific to the assumed granite quarry dust, Zone II natural sand, M30 binder content, water–binder ratio, and compaction quality. A dust with higher clay content, different mineralogy, more material below 75 µm, or higher absorption may require a lower replacement level. Likewise, mixes containing fly ash, slag, silica fume, recycled aggregate, fibers, or air entrainment require separate optimization.

Water absorption and sorptivity are screening indicators rather than a complete durability assessment. For aggressive exposure, additional tests should include rapid chloride migration or diffusion, electrical resistivity, carbonation depth, sulfate resistance, drying shrinkage, abrasion, and reinforcement corrosion. Long-term field trials are desirable to evaluate finishing, pumping, curing sensitivity, surface cracking, and variability between quarry production lots.

IX. CONCLUSIONS AND RECOMMENDATIONS

Within the defined M30 experimental framework and based on the illustrative dataset, the following conclusions are obtained:

- Quarry dust is technically promising as a partial replacement for natural sand when its source, grading, fines content, absorption, and deleterious materials are controlled.
- Workability decreases continuously with increasing replacement; the example slump falls from 92 mm at 0% to 54 mm at 50%. Water should not be added informally to recover slump.
- Mechanical properties improve up to a moderate level. The illustrative 30% mix reaches 44.1 MPa at 28 days, 14.2% above the control, with corresponding gains in splitting tensile and flexural strength.
- Water absorption and sorptivity are minimized at 30% in the example, supporting the interpretation of improved packing and reduced connected porosity.
- At replacement levels above 30–40%, workability loss, greater paste demand, agglomeration, and compaction sensitivity reduce the benefit of the fine particles.
- The quadratic fit predicts an illustrative optimum of approximately 28.6%, while the multi-criteria index also selects 30%. A practical field trial range of 20–30% is recommended before project approval.
- At 30% replacement, the adopted mix conserves approximately 206 kg of natural sand per cubic metre and uses an equal mass of quarry by-product.
- Final approval must be based on actual laboratory validation and applicable specifications; the numerical values in this manuscript should be replaced with measured data.

9.1 Recommended future work

- Test intermediate replacement levels near the optimum and apply response-surface design.
- Quantify chloride penetration, carbonation, shrinkage, abrasion, and reinforcement corrosion.
- Use SEM, XRD, and pore-size analysis to distinguish filler effects from mineral reactivity.
- Develop source-specific prediction models using particle shape, grading, fines content, and absorption as input variables.
- Complete a project-based life-cycle and cost assessment using measured transport and processing data.

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