

Development and Performance Assessment of Sustainable Self-Compacting Concrete Incorporating Fly Ash and Granite Waste as Alternative Cementitious and Aggregate Materials

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Abstract - Self-compacting concrete (SCC) can improve placement in congested structural members while reducing the need for mechanical vibration. This study investigates SCC incorporating Class F fly ash as a 30% cement replacement and granite waste as a partial replacement of natural fine aggregate at 20–60%. An ordinary Portland cement control and a fly-ash blended control were compared with seven granite-waste mixtures. Fresh-state performance was assessed using slump flow, while compressive strength was measured at 7, 28, 90, 180 and 365 days and split tensile and flexural strengths at 28, 90 and 180 days. All mixtures maintained satisfactory flowability, with slump-flow values of 745–770 mm. The F30G30 mixture produced the highest compressive strength at 28, 180 and 365 days, reaching 46.5, 59.0 and 64.2 MPa, respectively. Split tensile strength was also highest at F30G30, whereas flexural strength peaked at F30G35. The combined results indicate that approximately 30–35% granite-waste replacement with 30% fly ash provides a balanced fresh and hardened performance for the investigated SCC system.

Key Words: self-compacting concrete, fly ash, granite waste, slump flow, compressive strength, sustainable concrete.

1. INTRODUCTION

The construction sector relies heavily on Portland cement and natural aggregates, while cement manufacture and intensive extraction of river sand impose environmental and resource pressures. Self-compacting concrete offers an efficient response to difficult placement conditions because it flows through congested reinforcement and consolidates under its own weight. However, SCC commonly requires high powder content and careful chemical-admixture control, creating an opportunity for supplementary cementitious materials and mineral residues to replace conventional constituents.

Class F fly ash is a widely used supplementary cementitious material. Its fine, predominantly spherical particles can improve particle packing and reduce inter-particle friction, while its pozzolanic contribution

becomes more significant with curing age. Granite processing, in contrast, generates a fine mineral residue that can be incorporated as a fine-aggregate substitute. Its angular and relatively rough particles may improve mechanical interlocking, but excessive replacement can increase surface area, water demand and friction. The engineering challenge is therefore to identify a replacement range that simultaneously satisfies fresh-state SCC requirements and hardened mechanical performance.

The present investigation evaluates a controlled SCC mixture family in which 30% of the cementitious binder is replaced by Class F fly ash and natural fine aggregate is progressively replaced by granite waste. The study considers workability, compressive strength, split tensile strength and flexural strength so that the optimum composition is assessed from a combined structural-performance perspective rather than from a single strength parameter.

2. LITERATURE REVIEW AND RESEARCH GAP

Previous research has established the value of mineral and industrial residues in sustainable concrete. Studies on granite waste have reported that stone-processing residues can act as fine mineral constituents or aggregate replacements and can improve packing and strength when used at controlled levels [3], [5], [7], [11], [18], [21]. Research on fly ash and other supplementary cementitious materials has similarly demonstrated benefits in SCC rheology, later-age strength and durability, although the response depends strongly on binder composition and replacement level [4], [12], [20], [43].

The literature also indicates that waste-derived fine materials do not provide unlimited benefits. Increasing replacement can raise specific surface area, alter water demand and increase inter-particle friction, leading to reductions in workability or mechanical performance beyond an optimum range. Studies of sustainable SCC and stone-processing residues consequently emphasize controlled replacement and simultaneous evaluation of fresh and hardened properties rather than assessment of one parameter in isolation [8], [10], [13], [15], [27].

A further consideration is the time-dependent response of fly-ash systems. Later-age strength may differ substantially from early-age behaviour because pozzolanic reactions develop progressively. The research gap addressed here is the systematic assessment of a fixed 30% fly-ash binder combined with progressively varied granite-waste replacement in SCC, with performance tracked through workability, compressive, split tensile and flexural tests and multiple curing ages. This approach permits identification of a balanced replacement range for structural SCC while distinguishing the contribution of fly ash from the additional influence of granite waste.

3. MATERIALS AND METHODOLOGY

3.1 Materials and Mixture System

Ordinary Portland cement of 43 grade and Class F fly ash conforming to ASTM C618 were used as binder constituents. River sand classified as Zone II and 10 mm crushed basalt were used as conventional fine and coarse aggregates, respectively. Dry granite waste obtained from granite cutting operations was used as a partial replacement of natural fine aggregate. A polycarboxylate-ether-based superplasticizer was used to achieve the required SCC flowability.

Table 1: Physical properties and selected chemical composition of cement and fly ash

Property	Cement	Fly ash
Consistency (%)	27.0	–
Specific gravity	3.16	2.28
Soundness (mm)	1.0	–
Initial setting time (min)	120	–
Final setting time (min)	241	–
Specific surface area (m ² /kg)	297	353
SiO ₂ (%)	31.3	58.19
Al ₂ O ₃ (%)	3.49	26.93
Fe ₂ O ₃ (%)	3.3	4.27
CaO (%)	45.88	0.9
LOI (%)	3.97	0.45

Table 2: Physical properties and selected chemical composition of aggregates and granite waste

Property	Fine aggregate	Coarse aggregate (10 mm)	Granite waste
Fineness modulus	2.5	5.99	1.4
Water absorption (%)	1.0	0.4	4.49
Specific gravity	2.64	2.71	2.57
Crushing value (%)	–	24.46	–
Impact value (%)	–	24.72	–
SiO ₂ (%)	77.25	–	69.77
Al ₂ O ₃ (%)	6.14	–	10.74

Property	Fine aggregate	Coarse aggregate (10 mm)	Granite waste
Fe ₂ O ₃ (%)	1.12	–	1.8
CaO (%)	2.51	–	0.89
K ₂ O (%)	4.28	–	4.84

3.2 Mix Design and Identification

The mixture notation F30Gx denotes 30% replacement of cement by fly ash and x% replacement of natural fine aggregate by granite waste. F0G0 is the ordinary Portland cement control, F30G0 is the fly-ash blended control, and F30G20–F30G60 constitute the granite-waste series. The total binder content was maintained at 548.53 kg/m³ and the effective water-to-binder ratio was 0.35. The effective water content was 191.99 kg/m³, while total added water was adjusted to account for the higher absorption of granite waste.

$$\text{Fly ash} = 0.30 \times 548.53 = 164.56 \text{ kg/m}^3; \text{Cement} = 0.70 \times 548.53 = 383.97 \text{ kg/m}^3$$

$$\text{Effective water} = 0.35 \times 548.53 = 191.99 \text{ kg/m}^3$$

Table 3: Principal mixture proportions

Mix ID	Cement (kg/m ³)	Fly ash (kg/m ³)	Fine agg. (kg/m ³)	Granite waste (kg/m ³)	Coarse agg. (kg/m ³)	Water (kg/m ³)	SP (%)
F0G0	548.53	–	968.35	–	698.17	204.47	2.61
F30G0	383.97	164.56	968.35	–	698.17	204.47	0.82
F30G20	383.97	164.56	774.68	193.67	698.17	211.23	0.77
F30G25	383.97	164.56	726.26	242.09	698.17	212.92	0.74
F30G30	383.97	164.56	677.85	290.51	698.17	214.60	0.80
F30G35	383.97	164.56	629.43	338.92	698.17	216.29	0.93
F30G40	383.97	164.56	581.01	387.34	698.17	217.98	1.04
F30G50	383.97	164.56	484.18	484.18	698.17	221.36	1.21
F30G60	383.97	164.56	387.34	581.01	698.17	224.74	1.70

3.3 Specimen Preparation and Test Programme

The dry constituents were first mixed, followed by gradual addition of water and superplasticizer. Fresh flowability was checked before casting. Specimens were demoulded after approximately one day and water cured until the designated testing age.

Table 4: Specimen dimensions and experimental test programme

Test	Specimen	Curing ages	Standard basis
Workability slump flow	Fresh SCC	Fresh state	EFNARC SCC criteria
Compressive strength	150 × 150 × 150 mm cube	7, 28, 90, 180, 365 days	BIS 516
Split tensile strength	150 mm dia. × 300 mm cylinder	28, 90, 180 days	BIS 5816
Flexural strength	150 × 150 × 700 mm beam	28, 90, 180 days	BIS 516

Table 5: SCC slump-flow classification criteria

SCC class	Slump-flow diameter (mm)
SF1	550–650
SF2	660–750
SF3	760–850

3.4 Test Methods

Slump flow was measured by filling the slump cone with fresh SCC and lifting the cone vertically. The spread diameter was measured in two perpendicular directions and averaged. The target range for the mixture family was 750 ± 30 mm.

Compressive strength was determined from 150 mm cube specimens using the maximum load divided by the loaded area. The governing relation is:

$$f_c = P / A$$

where f_c is compressive strength in MPa, P is maximum load in N and A is the loaded area in mm^2 . Split tensile strength was measured on cylindrical specimens loaded diametrically.

$$f_t = 2P / (\pi LD)$$

where f_t is split tensile strength in MPa, P is maximum load, L is cylinder length and D is cylinder diameter. Flexural strength was determined from beam failure under the applicable bending arrangement.

$$f_r = PL / (bd^2)$$

where f_r is flexural strength in MPa, P is critical load, L is effective span, b is beam width and d is beam depth. Strength development was evaluated over the specified curing ages, and percentage variation was considered where useful for comparison with the control mixtures.

4. RESULTS AND DISCUSSION

4.1 Workability

The investigated SCC mixtures exhibited slump-flow values between 745 and 770 mm. The narrow range demonstrates that the combined effect of fly ash, granite-waste content and adjusted superplasticizer dosage successfully maintained fresh-state mobility. The fly-ash blended control and F30G30 recorded the highest spread of 770 mm, while the lowest value, 745 mm, occurred for the ordinary Portland cement control.

Table 6: Slump-flow workability results

Mix ID	Slump flow (mm)
F0G0	745
F30G0	770
F30G20	765
F30G25	765
F30G30	770
F30G35	755
F30G40	750
F30G50	755
F30G60	750

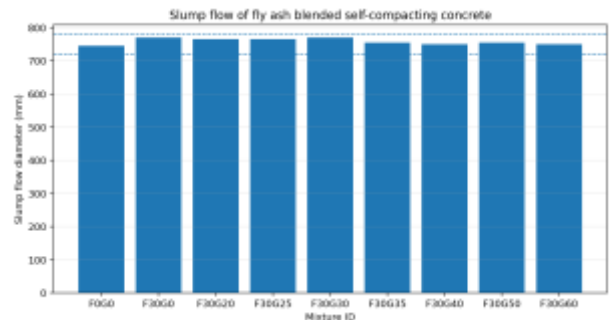


Fig. 1: Slump-flow workability of the investigated SCC mixtures

The results confirm that granite-waste replacement up to 60% did not produce a sharp loss of flowability when the admixture dosage was adjusted. This is significant for SCC because filling ability must be retained while waste-derived fine materials are introduced.

4.2 Compressive Strength

Compressive strength increased with curing age for every mixture, reflecting continued hydration and the progressive contribution of fly ash. The granite-waste series exhibited an initial improvement at moderate replacement followed by a reduction at high replacement. The improvement is consistent with filler action, particle packing and aggregate–paste interlocking, whereas excessive fine content increases surface area and can disturb paste distribution.

Table 7: Compressive strength results (MPa)

Mix ID	7 d	28 d	90 d	180 d	365 d
F0G0	34.3	45.7	50.9	54.4	57.3
F30G0	26.0	38.6	47.3	56.5	60.7
F30G20	27.3	41.6	48.4	56.8	62.1
F30G25	27.5	42.3	49.9	57.4	62.2
F30G30	29.4	46.5	52.2	59.0	64.2
F30G35	28.4	43.5	51.4	57.9	62.7
F30G40	26.0	38.9	47.8	56.5	61.9
F30G50	22.5	35.8	44.7	52.1	58.0
F30G60	20.9	32.5	41.9	49.6	54.3

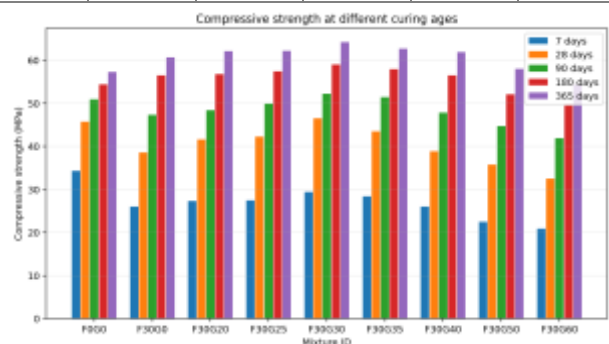


Fig. 2: Compressive strength at different curing ages

At 28 days, F30G30 reached 46.5 MPa, exceeding both the fly-ash control (38.6 MPa) and ordinary Portland cement control (45.7 MPa). At 180 days, F30G30 reached 59.0 MPa compared with 56.5 MPa for F30G0 and 54.4 MPa for F0G0. At 365 days, F30G30 attained 64.2 MPa, representing the highest later-age compressive strength of the investigated series. The result indicates that the combined binder and fine-

particle packing were most favourable near 30% granite-waste replacement.

Increasing granite waste beyond this range reduced strength progressively. F30G50 and F30G60 reached only 58.0 and 54.3 MPa at 365 days, respectively. The decline suggests that the beneficial filler effect has a practical limit; beyond the optimum, additional fine particles increase surface demand and reduce the efficiency of paste coating and packing.

4.3 Split Tensile Strength

Split tensile strength increased with curing age and was sensitive to the quality of the aggregate–paste interface. Moderate granite-waste contents improved the response, consistent with the angular and rough particle surfaces enhancing mechanical interlocking and crack resistance.

Table 8: Split tensile strength results (MPa)

Mix ID	28 d	90 d	180 d
F0G0	5.19	5.30	5.35
F30G0	4.65	4.99	5.43
F30G20	5.03	5.23	5.46
F30G25	5.11	5.34	5.54
F30G30	5.61	5.85	5.93
F30G35	5.38	5.49	5.77
F30G40	4.84	5.15	5.51
F30G50	4.69	5.03	5.46
F30G60	4.34	4.80	5.08

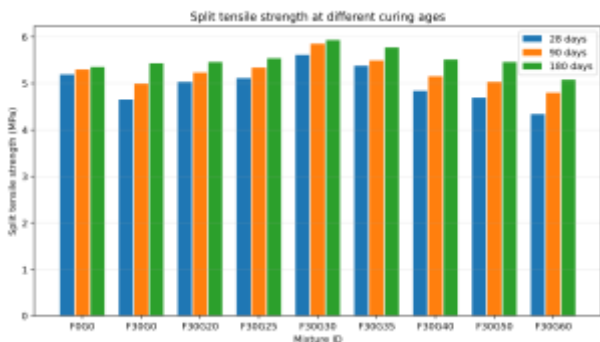


Fig. 3: Split tensile strength at different curing ages

F30G30 produced 5.61, 5.85 and 5.93 MPa at 28, 90 and 180 days, respectively, which were the highest values within the granite-waste series. At 60% granite waste, the corresponding values fell to 4.34, 4.80 and 5.08 MPa. The pattern indicates that moderate replacement provides a favourable balance between particle interlocking and continuity of the cementitious matrix.

4.4 Flexural Strength

Flexural strength showed a similar age-dependent increase, but its optimum occurred at a slightly higher granite-waste content than compressive strength. The rough and angular granite particles can improve interlocking and restrain crack development under bending, making the flexural response particularly sensitive to aggregate morphology.

Table 9: Flexural strength results (MPa)

Mix ID	28 d	90 d	180 d
F0G0	5.21	5.45	5.51
F30G0	4.80	5.24	5.59
F30G20	5.17	5.44	5.61
F30G25	5.40	5.58	5.66
F30G30	5.92	6.08	6.21
F30G35	5.95	6.08	6.25
F30G40	5.15	5.37	5.64
F30G50	4.89	5.30	5.61
F30G60	4.42	5.08	5.31

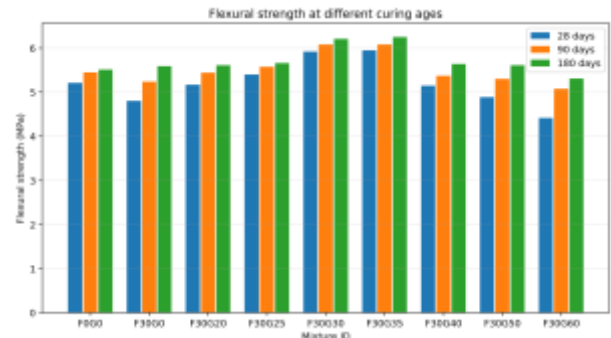


Fig. 4: Flexural strength at different curing ages

F30G35 gave the highest flexural strength, reaching 5.95 MPa at 28 days, 6.08 MPa at 90 days and 6.25 MPa at 180 days. This differs slightly from the compressive-strength optimum at F30G30, showing that the governing optimum can depend on the mechanical property being considered.

4.5 Integrated Engineering Assessment

The combined results show that the investigated SCC system has a practical optimum range rather than a single universal optimum. Workability remained satisfactory throughout the mixture family. Compressive and split tensile strength were most favourable near F30G30, while flexural strength peaked at F30G35. Accordingly, a granite-waste replacement range of approximately 30–35% with 30% fly ash provides the most balanced response for the tested system.

From a structural perspective, compressive strength governs the primary load-bearing classification, while split tensile and flexural strengths provide complementary information on cracking and tension-zone behaviour. The results indicate that sustainable SCC can maintain substantial later-age strength while simultaneously reducing reliance on Portland cement and natural fine aggregate. The use of industrial residues is therefore most effective when replacement is controlled to preserve particle packing, paste continuity and fresh-state flow.

5. CONCLUSIONS AND FUTURE SCOPE

- Class F fly ash and granite waste can be incorporated successfully into SCC while maintaining the required high flowability.
- Slump-flow values remained between 745 and 770 mm, demonstrating effective fresh-state control through mixture proportioning and superplasticizer adjustment.

- The 30% fly-ash control developed lower early-age compressive strength than the ordinary Portland cement control, but its later-age performance improved substantially.
- Moderate granite-waste replacement improved compressive strength through filler action, particle packing and aggregate–paste interlocking, whereas higher replacement progressively reduced strength.
- F30G30 produced the most favourable compressive response, reaching 46.5 MPa at 28 days, 59.0 MPa at 180 days and 64.2 MPa at 365 days.
- Split tensile strength was highest near 30% granite-waste replacement, while flexural strength reached its maximum at F30G35.
- The combined performance indicates that approximately 30–35% granite-waste replacement with 30% fly ash provides a balanced engineering response for the investigated SCC system.
- The material combination offers a route to reduce Portland cement consumption and natural fine-aggregate demand while retaining structural performance.

Future Scope

Future work should examine chloride penetration, carbonation, sulphate exposure, water absorption, shrinkage, creep, modulus of elasticity and fracture energy for the optimum replacement range. Structural-scale studies on reinforced beams, slabs and columns, together with reinforcement bond testing, can establish member-level applicability. Life-cycle assessment and cost analysis can further quantify the environmental and economic benefits of the combined use of fly ash and granite waste.

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