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Strength and Durability Evaluation of Self-Consolidating Concrete for Rigid Pavement Applications

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Abstract

Conventional pavement quality concrete (PQC) needs heavy vibration because of its low workability, while conventional self-compacting concrete (SCC) needs high cement contents. This study develops two innovative self-consolidating concretes for rigid pavements: low-fines self-consolidating concrete (LF-SCC) for fixed-form paving and semi-flowable self-consolidating concrete (SF-SCC) for slip-form paving. Fly ash (FA), sugarcane bagasse ash (SCBA) and rice husk ash (RHA) replaced cement at 10–50%, giving 32 mixes (16 LF-SCC and 16 SF-SCC). Fresh properties and compressive, splitting tensile and flexural strengths were determined at 7, 28, 56 and 90 days and assessed against IRC:44-2017 requirements. All LF-SCC mixes met the EFNARC SF1 fresh-state criteria (slump flow 640–650 mm), and all SF-SCC mixes met the semi-flowable criteria (slump 152–176 mm, green strength 1.32–1.82 kPa). Strength generally increased up to 20% replacement and declined beyond it; the highest 28-day compressive strengths of LF-SCC were 53.48 MPa (20% RHA) and 53.04 MPa (20% SCBA). All 32 mixes satisfied the requirements for village roads, while 12 of 16 LF-SCC and 13 of 16 SF-SCC mixes achieved at least 40 MPa compressive and 4.5 MPa flexural strength at 28 days for urban roads. A 20% replacement level is recommended for SCBA and RHA in both concretes.

Keywords: Low-fines self-consolidating concrete; Semi-flowable self-consolidating concrete; Concrete pavement; Fly ash; Sugarcane bagasse ash; Rice husk ash

1. Introduction

India's road network is the second largest in the world, and rigid pavements are increasingly preferred for their strength, durability and low maintenance. Conventional PQC has a slump of only 0–50 mm and needs intense vibration, which consumes energy, slows construction and, in slip-form paving, leaves vibratory trails, segregation and dowel-bar marks on the surface. SCC compacts under its own weight, but conventional SCC needs 450–650 kg/m³ of cement, which raises cost and CO_2 emissions, and its high flowability cannot hold a camber or grade in slip-form paving.

Two newer concretes address these limitations. Low-fines SCC (LF-SCC) has a lower binder content and a flow of 600–650 mm, suiting fixed-form paving. Semi-flowable SCC (SF-SCC) combines self-consolidation with shape stability in the fresh state, suiting slip-form paving [6]. Replacing part of the cement with pozzolanic wastes such as FA, SCBA and RHA can further reduce cement demand and dispose of industrial and agricultural wastes. The objectives of this study are to (i) develop LF-SCC and SF-SCC mixes with FA, SCBA and RHA at 10–50% cement replacement, (ii) evaluate their fresh and strength properties, and (iii) assess their suitability for village and urban rigid pavements as per IRC:44-2017 [12].

2. Literature Review

Reviews of SCC with supplementary cementitious materials report benefits for fresh, mechanical, durability and sustainability performance [1]. RHA improves strength and durability through its pozzolanic reaction [2], [8], and blending RHA with calcined clay has been examined for SCC production [10]. Bagasse ash shows strength, durability and microstructural potential as a cement replacement [3], [9]. For pavements, Kannur and Chore developed LF-SCC with FA and bagasse ash [4] and with RHA, where up to 20% RHA improved performance and the mixes suited road pavements [5]. They also reviewed SF-SCC for slip-form construction of rigid pavements [6] and assessed SF-SCC with SCBA [7]. Industrial wastes have likewise been used as cement replacements in pavement concrete [11]. However, comparatively little work evaluates FA, SCBA and RHA side by side in both LF-SCC and SF-SCC against Indian pavement specifications, which is the focus of this study.

3. Materials and Methodology

Materials. OPC-43 conforming to IS 269 (2015) was used. Natural river sand from the Nagavalli river (Zone II, specific gravity 2.62, fineness modulus 2.77) and crushed coarse aggregates of 10 mm and 20 mm nominal size (specific gravity 2.77 and 2.65) were graded to IRC:44-2017 with a maximum size of 12.5 mm. Class F fly ash was obtained from NTPC Simhadri, Parwada. Raw SCBA from the Sangivalasa jute mill and raw RHA from a local rice mill were ball-milled at

50 rpm for 180 minutes and sieved through a 75 µm sieve; RHA was oven-dried at 100 °C before milling. A polycarboxylate ether superplasticizer (HRWR), a viscosity modifying admixture (VMA) and an SBR bonding agent were used. The cementitious materials are shown in Fig. 1 and their properties in Table 1.



Fig. 1. Cementitious materials used: (a) cement, (b) FA, (c) SCBA, (d) RHA

Table 1. Physical parameters and chemical composition of cementitious materials

Property	Cement	FA	SCBA	RHA
Specific gravity	3.13	2.2	2.18	1.98
Specific surface area (m^2/kg)	312	415	320	510
Loss on ignition (%)	2.03	1.21	8.64	1.1
SiO_2 (%)	29.86	58.10	69.82	88.91
Fe_2O_3 (%)	3.16	7.92	4.21	0.61
Al_2O_3 (%)	10.93	26.74	4.59	0.29
CaO (%)	50.84	3.10	1.82	0.48
MgO (%)	1.58	2.16	1.08	0.37
Alkalies ($Na_2O + K_2O$) (%)	1.71	1.76	1.16	0.81
SO_3 (%)	1.97	0.26	0.16	0.14
$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)	43.95	92.76	78.62	89.81

The overall methodology is shown in Fig. 3.

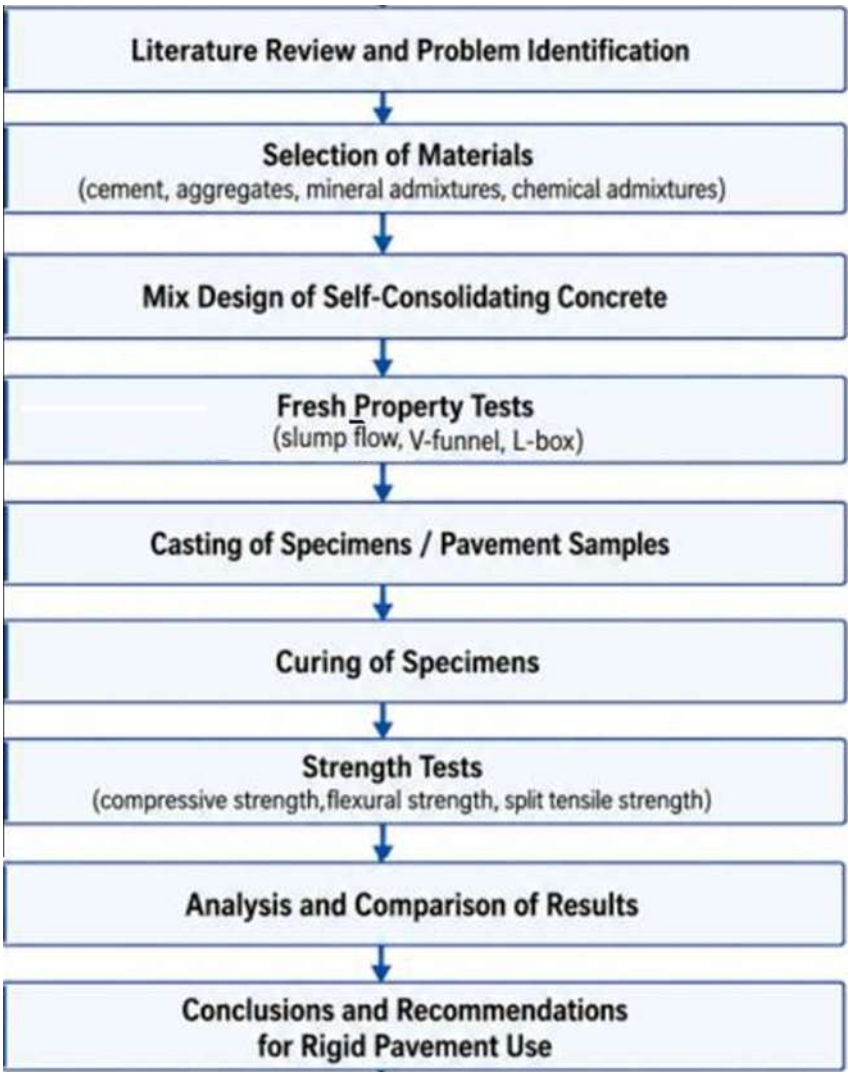


Fig. 3. Flow of the work

Mix proportions. Each ash replaced cement at 10%, 20%, 30%, 40% and 50%, giving 16 LF-SCC mixes (LFC, LFF1–LFF5, LFB1–LFB5, LFR1–LFR5) and 16 SF-SCC mixes (SFC, SFF1–SFF5, SFB1–SFB5, SFR1–SFR5), where F, B and R denote FA, SCBA and RHA. LF-SCC used a total binder of 450 kg/m³, a fine-to-coarse aggregate ratio of 45:55 and 0.10% VMA, with w/b and HRWR adjusted by trials to reach a slump flow of about 650 mm. SF-SCC was proportioned by the performance-based method of Lomboy et al., with 475 kg/m³ binder and 0.1% VMA. The key proportions are given in Table 2.

Table 2. Mix proportions of LF-SCC (binder 450 kg/m³) and SF-SCC

Mix (LF/SF)	Replacement (%)	LF w/b	LF SBR	LF HRWR (%)	SF OPC (kg/m³)	SF ash (kg/m³)	SF w/b	SF HRWR (%)
LFC/SFC	0	0.37	0%	0.75	475	0	0.35	0.70
LFF1/SFF1	FA 10	0.36	0%	0.75	427.5	47.5	0.35	0.73
LFF2/SFF2	FA 20	0.35	1%	0.75	380	95	0.34	0.75
LFF3/SFF3	FA 30	0.33	2%	0.80	332.5	142.5	0.33	0.77
LFF4/SFF4	FA 40	0.30	3%	0.85	285	190	0.32	0.80
LFF5/SFF5	FA 50	0.30	3%	0.85	237.5	237.5	0.31	0.82
LFB1/SFB1	SCBA 10	0.37	0%	0.85	427.5	47.5	0.36	0.75
LFB2/SFB2	SCBA 20	0.37	1%	0.90	380	95	0.36	0.78
LFB3/SFB3	SCBA 30	0.37	2%	0.95	332.5	142.5	0.35	0.85
LFB4/SFB4	SCBA 40	0.37	3%	1.10	285	190	0.34	0.92
LFB5/SFB5	SCBA 50	0.37	3%	1.15	237.5	237.5	0.33	1.00
LFR1/SFR1	RHA 10	0.38	0%	1.65	427.5	47.5	0.380	1.25
LFR2/SFR2	RHA 20	0.38	0%	1.80	380	95	0.380	1.40
LFR3/SFR3	RHA 30	0.38	0%	2.10	332.5	142.5	0.380	1.65
LFR4/SFR4	RHA 40	0.38	0%	2.20	285	190	0.380	1.80
LFR5/SFR5	RHA 50	0.38	0%	2.35	237.5	237.5	0.380	2.10

Testing. Fresh LF-SCC was tested for slump flow, T50, V-funnel and L-box as per EFNARC (2005); fresh SF-SCC for slump, flow, compaction factor and green strength, with a mini-paver used to extrude trial slabs (Fig. 2). Compressive strength (100 mm cubes, IS 516), splitting tensile strength (100 × 200 mm cylinders, IS 5816) and flexural strength (100 × 100 × 500 mm prisms, IS 516) were determined after 7, 28, 56 and 90 days of water curing at 27 °C. For SF-SCC, 75 mm cores drilled from the extruded slabs were also tested and averaged with cube results. The results were compared with the IRC:44-2017 targets [12]: a minimum 7-day compressive strength of 20 MPa, 28-day compressive strengths of 30 MPa (village roads) and 40 MPa (urban roads), and 28-day flexural strengths of 3.8 MPa and 4.5 MPa respectively.



Fig. 2. Hardened slab extruded from the mini-paver (SFB2)

4. Results and Discussion

4.1 Fresh Properties

All LF-SCC mixes satisfied the EFNARC SF1 requirements (Table 3). Increasing FA improved flowability through the ball-bearing effect of its spherical particles, lowering the V-funnel time from 10.83 s to 9.45 s. SCBA and RHA reduced workability: V-funnel times rose to 15.1 s and 11.97 s at 50% replacement, and the HRWR demand of RHA mixes rose from 1.65% to 2.35%. The standard consistency of cement–RHA pastes increased from 32.5% for plain OPC to 60.4% at 50% RHA, confirming the high water demand of the porous, high-surface-area RHA. All SF-SCC mixes met the semi-flowable criteria, with slump of 152–176 mm, flow of 282–316 mm, green strength of 1.32–1.82 kPa and a compaction factor of at least 0.98, and the mini-paver slabs held their shape (Fig. 2).

Table 3. Fresh properties of LF-SCC

Mix reference	Slump flow (mm)	V-funnel (s)	L-box (ratio)	T50 (s)
LFC	645	10.83	0.84	4.89
LFF1	645	10.61	0.85	4.62
LFF2	645	9.92	0.85	4.51
LFF3	650	9.68	0.86	4.36
LFF4	650	9.55	0.86	4.58
LFF5	650	9.45	0.87	4.29
LFB1	645	11	0.9	4.46
LFB2	640	12	0.87	4.86
LFB3	640	13.21	0.85	4.98
LFB4	640	14.89	0.83	5.1
LFB5	640	15.1	0.81	5.27
LFR1	650	9.2	0.82	4.91
LFR2	645	9.16	0.81	5.26
LFR3	640	10.58	0.8	5.46
LFR4	640	11.32	0.79	6.23
LFR5	640	11.97	0.77	6.82
EFNARC recommendation	550–650	5 to 25	Min 0.65	Min 2

4.2 Strength of LF-SCC

The compressive strengths of LF-SCC are given in Table 4 and the splitting tensile and flexural strengths in Table 5. For all three ashes, strength increased up to 20% replacement and declined beyond it. At 28 days, 10% and 20% FA raised compressive strength by 0.75% and 2.04% over the control (50.57 MPa), while 30–50% FA reduced it by 12.91–25.37%; FA mixes gained strength steadily at 56 and 90 days owing to slow pozzolanic reaction. SCBA at 20% gave 53.04 MPa (+4.98%) and RHA at 20% gave the highest value of 53.48 MPa (+5.73%), attributed to pore refinement and additional C–S–H formation from their reactive silica. At higher contents, dilution of the cement, the porous ash particles and greater water demand reduced strength, most severely with 50% SCBA (33.80 MPa).

Splitting tensile and flexural strengths followed the same trend. At 28 days, 20% SCBA gave the highest flexural strength of 5.66 MPa (13.85% above the control) and 20% FA raised splitting tensile strength by 6.06%. Every LF-SCC mix exceeded 20 MPa at 7 days (minimum 25.80 MPa) and the village-road targets of 30 MPa and 3.8 MPa at 28 days. All mixes except LFF4, LFF5, LFB4 and LFB5 also exceeded 40 MPa, and all except LFF5 (4.31 MPa) exceeded 4.5 MPa in flexure, so 12 of the 16 LF-SCC mixes qualify for urban roads.

Table 4. Compressive strength (MPa) of LF-SCC

Mix	7 Day	28 Day	56 Day	90 Day
LFC	34.55	50.57	53.82	59.28
LFF1	32.56	50.95	55.34	62.10
LFF2	31.69	51.60	58.44	63.60
LFF3	30.49	44.04	49.32	59.28
LFF4	29.11	39.12	47.16	53.52
LFF5	25.80	37.74	46.66	50.28
LFB1	41.69	52.08	55.45	61.26
LFB2	42.73	53.04	58.21	63.37
LFB3	32.94	46.46	48.94	49.44
LFB4	30.22	38.74	43.08	46.32
LFB5	26.50	33.80	35.15	37.10
LFR1	37.57	51.86	55.94	57.97
LFR2	40.16	53.48	58.38	60.74
LFR3	32.77	48.94	55.00	58.77
LFR4	30.89	45.36	49.98	52.31
LFR5	27.50	42.42	46.82	48.89

Table 5. Splitting tensile and flexural strength (MPa) of LF-SCC

Mix	STS 7 d	STS 28 d	STS 56 d	STS 90 d	FS 7 d	FS 28 d	FS 56 d	FS 90 d
LFC	2.93	3.63	3.89	4.23	4.34	4.98	5.15	5.35
LFF1	2.81	3.75	3.95	4.30	4.42	5.10	5.65	5.85
LFF2	3.34	3.85	4.19	4.37	4.58	5.34	6.12	6.31
LFF3	2.82	3.55	3.85	4.21	3.94	4.63	5.05	5.10
LFF4	2.62	3.33	3.76	4.01	3.66	4.54	4.81	4.85
LFF5	2.59	3.28	3.74	3.89	3.62	4.31	4.42	4.48
LFB1	3.13	3.80	4.01	4.40	4.38	5.52	6.12	6.29
LFB2	3.20	3.86	4.10	4.49	4.62	5.66	6.14	6.38
LFB3	2.42	2.98	3.25	3.43	4.12	4.78	4.95	5.00
LFB4	1.73	2.48	2.78	3.08	4.04	4.67	4.76	4.82
LFB5	1.65	2.35	2.38	2.45	3.60	4.58	4.63	4.68
LFR1	3.00	3.69	3.92	4.34	4.42	5.03	5.23	5.39
LFR2	3.02	3.72	3.98	4.46	4.56	5.10	5.31	5.45
LFR3	2.56	3.57	3.81	4.06	4.04	4.89	5.07	5.25
LFR4	2.19	3.41	3.71	4.03	3.84	4.63	4.83	5.13
LFR5	2.06	3.17	3.54	3.81	3.75	4.59	4.76	4.95

4.3 Strength of SF-SCC

The compressive strengths of SF-SCC are shown in Fig. 4. FA reduced early strength, with 7-day reductions of 1.44–30.24% and 28-day reductions of 2.50–27.35% relative to the control (SFC), because FA reacts slowly. At later ages, 10% and 20% FA exceeded the control by 4.40% and 3.07% at 56 days and by 8.34% and 6.35% at 90 days. SCBA increased the 28-day strength by 8.36% at 10% and 16.95% at 20%, while 50% SCBA gave 38.91 MPa. RHA was the most effective: 20% RHA raised the 28-day strength by 24.52% and the 90-day strength by 25.90%, and mixes with up to 30% RHA remained stronger than the control.

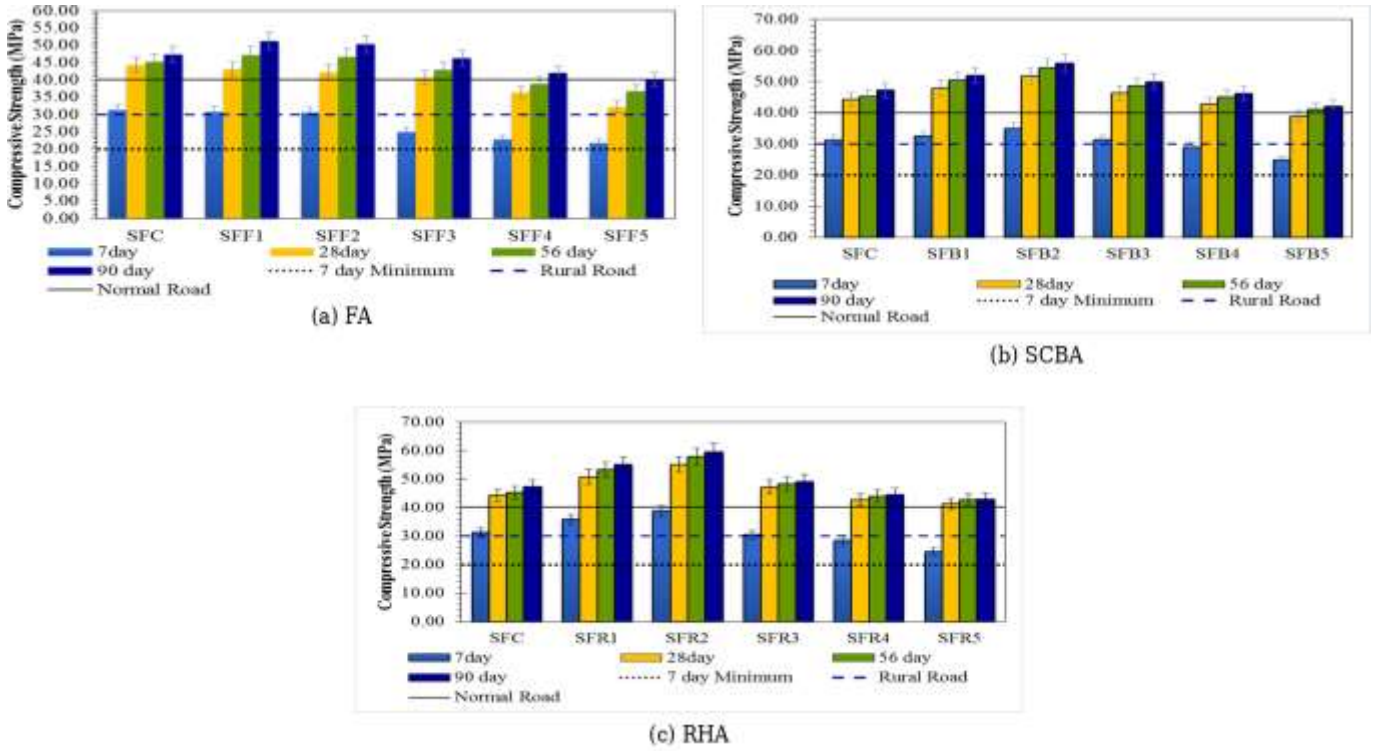


Fig. 4. Compressive strength of SF-SCC with (a) FA, (b) SCBA and (c) RHA

Splitting tensile strength showed the same trends, ranging from 3.30 MPa (SFB5) to 4.90 MPa (SFB2) for SCBA and from 3.60 MPa to 5.00 MPa at 28 days for RHA, with 20% RHA highest. Flexural strengths are shown in Fig. 5. At 28 days, 10% and 20% SCBA gave 1.12 and 1.16 times the control flexural strength, and 20% RHA raised it by 12%. All SF-SCC mixes exceeded 20 MPa at 7 days and the village-road targets of 30 MPa and 3.8 MPa at 28 days. SFF4 and SFF5 fell below 40 MPa in compression, and SFB5 reached only 38.91 MPa and 4.02 MPa, so 13 of the 16 SF-SCC mixes qualify for urban roads.

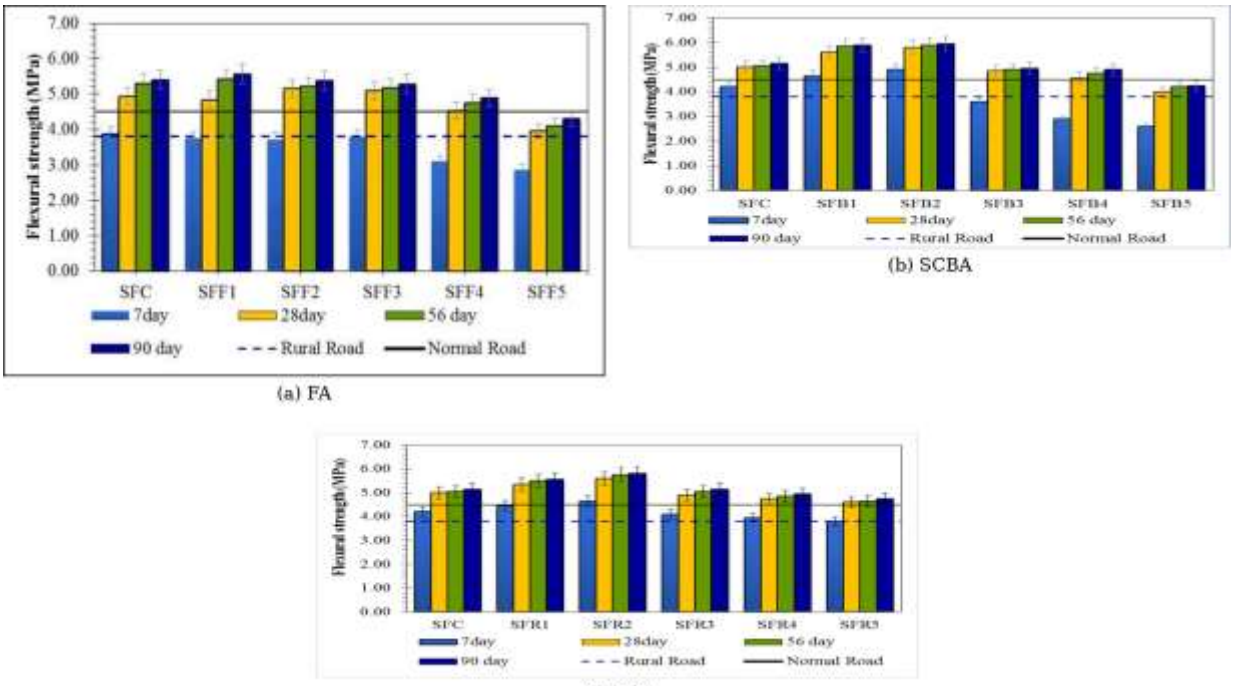


Fig. 5. Flexural strength of SF-SCC with (a) FA, (b) SCBA and (c) RHA

4.4 Suitability and Optimum Replacement

Across both concretes, about 20% replacement was optimum for SCBA and RHA, and FA performed best at 10–20%, with its benefit appearing mainly at later ages. All 32 mixes are suitable for village-road pavements, while 25 of the 32 meet the urban-road criteria of IRC:44-2017. LF-SCC with up to 20% ash therefore suits fixed-form paving of urban

roads, and SF-SCC with 20% SCBA or RHA offers vibration-free slip-form paving with strength well above the urban targets and reduced cement content.

5. Conclusions

1. FA, SCBA and RHA can replace 10–50% of cement in LF-SCC and SF-SCC while meeting the respective fresh-state criteria, reducing cement consumption and utilising industrial and agricultural wastes.
2. FA improved the flowability of LF-SCC, whereas SCBA and RHA reduced workability and increased HRWR demand because of their porous particles and high specific surface area.
3. Compressive, splitting tensile and flexural strengths generally increased up to 20% replacement and decreased beyond it; FA mixes showed significant later-age strength gain.
4. The highest 28-day compressive strengths of LF-SCC were 53.48 MPa with 20% RHA and 53.04 MPa with 20% SCBA; in SF-SCC, 20% RHA increased the 28-day strength by 24.52% over the control.
5. All 32 mixes satisfy IRC:44-2017 requirements for village roads, and 12 LF-SCC and 13 SF-SCC mixes satisfy those for urban roads (40 MPa compressive and 4.5 MPa flexural strength at 28 days). A 20% replacement of cement with SCBA or RHA is recommended.

Durability, shrinkage and field performance of the optimum mixes should be evaluated before large-scale adoption.

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