

Advanced Performance Evaluation of Self-Compacting Concrete Incorporating Marine Sand and Ternary Cementitious Binder Systems.

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Abstract - This study investigates M40-grade self-compacting concrete incorporating partial sea-sand replacement within a ternary binder comprising ordinary Portland cement, fly ash and ground granulated blast furnace slag. Six mixtures were examined using manufactured sand and river sand as reference fine aggregates, with sea sand introduced at 0%, 10% and 50% replacement levels. The binder was maintained at 65% cement, 30% fly ash and 5% ground granulated blast furnace slag, with a total cementitious content of 590 kg/m³. Fresh-state performance was assessed through slump-flow spread, while hardened performance was evaluated using compressive strength, split tensile strength and flexural strength. The results show a progressive reduction in flow spread with increasing sea-sand replacement, although all mixtures retained high-flow self-compacting characteristics. At 28 days, compressive strength ranged from 50.5 to 64.0 MPa, exceeding the 48 MPa target mean strength for all mixtures. Strength development continued to 90 days, with the 50% sea-sand mixtures showing particularly favourable later-age compressive and flexural performance. The findings demonstrate that partial sea-sand replacement can be technically feasible in the investigated ternary-binder self-compacting concrete system when aggregate proportioning and fresh-state flow are appropriately controlled.

Key Words: self-compacting concrete, sea sand, ternary binder, fly ash, GGBS, mechanical strength.

1. INTRODUCTION

Concrete remains a principal structural material because of its strength, versatility and adaptability to diverse structural forms. Increasing demand for construction materials, together with environmental concerns associated with intensive extraction of natural river sand, has encouraged investigation of alternative fine aggregates. Sea sand is attractive in regions where marine resources are accessible, but its particle characteristics, soluble salts, shell content and grading can alter fresh-state rheology and hardened performance. The response is therefore strongly dependent on the complete concrete system rather than on aggregate replacement alone.

Self-compacting concrete (SCC) is designed to flow under its own weight, fill congested formwork and pass around reinforcement without conventional mechanical vibration. Its performance depends on paste volume, aggregate packing, water-to-binder ratio and chemical admixture dosage. Previous studies have reported both beneficial and

adverse effects of sea sand on SCC flowability, demonstrating that the influence is system-specific [1–5], [27], [32], [39]. Research on seawater–sea-sand concrete further shows that binder composition and marine aggregate characteristics interact to govern mechanical and durability-related behaviour [3], [11], [12], [16], [18], [24], [26], [38].

Supplementary cementitious materials provide an additional route for improving material efficiency while reducing the Portland-cement fraction. Fly ash and ground granulated blast furnace slag (GGBS) can modify fresh rheology and contribute to later-age strength development. Studies on triple-blend and sustainable SCC support the use of blended binders when the proportions and aggregate system are controlled [4], [5], [17], [23], [33]. Structural investigations using sea-sand concrete with fibre-reinforced polymer and textile reinforcement also indicate the potential for progression from material development toward structural applications, while emphasizing the need to evaluate bond, cracking, member capacity and durability separately [8], [10], [21], [28–31], [35–37].

The present investigation addresses the need for a controlled comparison of partial sea-sand replacement within one M40 SCC system. Six mixtures were developed around a constant ternary binder and two reference fine-aggregate families. The study focuses on four directly relevant performance measures: slump-flow spread, compressive strength, split tensile strength and flexural strength. The objective is to establish how 10% and 50% sea-sand replacement influence fresh and hardened properties and to identify mixtures warranting further structural investigation.

2. MATERIALS AND EXPERIMENTAL PROGRAM

2.1 Materials

The concrete incorporated 53-grade ordinary Portland cement (OPC), Class F fly ash, GGBS, manufactured sand, river sand, sea sand, 10 mm nominal maximum-size coarse aggregate, water and a superplasticizer. The ternary binder was maintained at 65% OPC, 30% fly ash and 5% GGBS by mass of total cementitious material. The total binder content was 590 kg/m³, comprising 383.5 kg/m³ OPC, 177 kg/m³ fly ash and 29.5 kg/m³ GGBS. The selected water-to-binder ratio for mix development was approximately

0.336, while the final water contents were 208.34–211.31 L/m³ and the superplasticizer dosage was 5.06 L/m³.

2.2 Mix Proportioning and Mixture Matrix

The target characteristic strength was M40, with a target mean strength of approximately 48 MPa obtained from 40 + 1.65(5). Two reference aggregate systems were adopted: manufactured sand and river sand. Sea sand replaced the reference fine aggregate at 10% and 50% by mass, producing six mixtures: TMSM100, TMSM90, TMSM50, TMSR100, TMSR90 and TMSR50. The ternary binder, admixture dosage and principal coarse-aggregate system were kept constant within each aggregate family to isolate the effect of fine-aggregate composition.

Table 1. Mix proportions of the six concrete mixtures (kg/m³, except water and superplasticizer)

Mix	Binder (kg/m ³)	C.A. (kg/m ³)	Fine aggregate (kg/m ³)	Water (L/m ³)	S P (L/m ³)
TMSM 100	383.5 / 177 / 29.5	751.6 3	M-sand 754.26	211.31	5.06
TMSM 90	383.5 / 177 / 29.5	751.6 3	M-sand 678.83 + sea 75.43	211.31	5.06
TMSM 50	383.5 / 177 / 29.5	751.6 3	M-sand 377.13 + sea 377.13	211.31	5.06
TMSR 100	383.5 / 177 / 29.5	782.6 4	River sand 781.86	208.34	5.06
TMSR 90	383.5 / 177 / 29.5	782.6 4	River 703.67 + sea 78.19	208.34	5.06
TMSR 50	383.5 / 177 / 29.5	782.6 4	River 390.93 + sea 390.93	208.34	5.06

Table 2. Binder composition and trial-batch basis

Component	Quantity	Unit	Basis / role
Total cementitious material	590	kg/m ³	100%
OPC	383.5	kg/m ³	65%
Fly ash	177	kg/m ³	30%
GGBS	29.5	kg/m ³	5%
Coarse aggregate – M-sand series	751.63	kg/m ³	Common within series
Coarse aggregate – river-sand series	782.64	kg/m ³	Common within series
Superplasticizer	5.06	L/m ³	All six mixtures
Water	208.34–211.31	L/m ³	Final mix proportions

2.3 Specimen Preparation and Curing

Fresh SCC was prepared using the selected proportions and placed into three specimen geometries. Compressive strength was evaluated using 100 mm cubes, split tensile strength using 150 × 300 mm cylinders, and flexural strength using 100 × 100 × 500 mm beams. Specimens were demoulded after initial setting and water cured. Compressive strength was evaluated at 3, 7, 28, 56 and 90 days, whereas split tensile and flexural strength were evaluated at 28, 56 and 90 days.

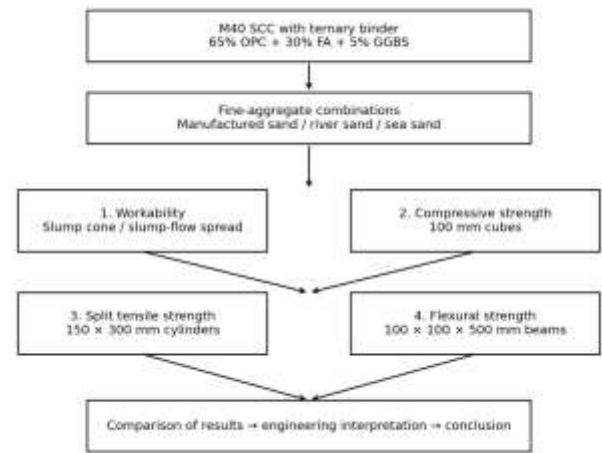


Fig. 1. Experimental sequence for the four performance tests.



Fig. 2. Representative specimen preparation and water-curing stages.

2.4 Test Procedures

Workability was measured using the slump-flow configuration. The cone was filled with fresh SCC, lifted vertically and the spread diameter was measured. The reported values are spread diameters rather than conventional subsidence-slump heights. Compressive strength was calculated from the maximum cube load divided by the loaded area, with a 100 × 100 mm loaded area. Split tensile strength was calculated using $f_t = 2P/(\pi LD)$, where P is the maximum load, L is the cylinder length and D is the cylinder diameter. Flexural strength was obtained from the maximum beam load using the applicable loading arrangement. Failure patterns were also observed for the hardened tests.

3. RESULTS AND DISCUSSION

3.1 Workability

Table 3. Slump-flow spread of the six SCC mixtures

Mix	Fine-aggregate composition	Spread (mm)
TMSM 100	100% manufactured sand	740
TMSM 90	90% manufactured sand + 10% sea sand	710
TMSM 50	50% manufactured sand + 50% sea sand	700
TMSR1 00	100% river sand	690
TMSR9 0	90% river sand + 10% sea sand	685
TMSR5 0	50% river sand + 50% sea sand	680

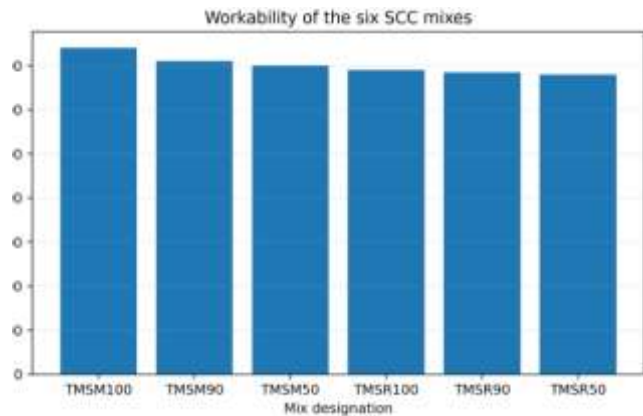


Fig. 3. Workability results of the six SCC mixtures.

TMSM100 produced the highest spread of 740 mm. Introducing 10% and 50% sea sand reduced the spread to 710 and 700 mm, corresponding to reductions of about 4.1% and 5.4%, respectively. The river-sand series showed lower absolute spreads, but the reduction with sea-sand replacement was much smaller: from 690 mm for TMSR100 to 685 and 680 mm for TMSR90 and TMSR50. This difference indicates that the workability response depends on the complete fine-aggregate packing system rather than only on the percentage of sea sand. From a construction perspective, the reduction in flow should be considered when SCC is intended for heavily reinforced members.

3.2 Compressive Strength

Table 4. Compressive strength development (MPa)

Age (d)	TMS M100	TMS M90	TMS M50	TMS R100	TMS R90	TMS R50
3	34.0	31.0	31.0	40.5	42.5	35.5
7	42.5	40.0	37.0	46.5	49.5	42.5
28	53.5	51.5	50.5	59.0	57.5	64.0
56	58.5	55.0	56.5	63.5	59.0	67.0
90	64.5	60.5	64.8	65.5	62.0	67.0

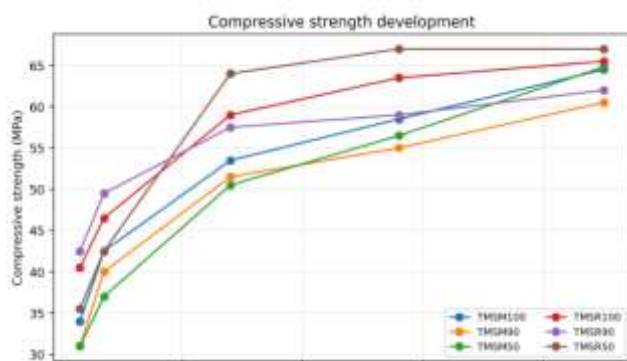


Fig. 4. Compressive strength development with curing age.

All six mixtures show continuous compressive-strength development with curing age. At 28 days, strengths ranged from 50.5 to 64.0 MPa, and therefore all mixtures exceeded the 48 MPa target mean strength. TMSR50 recorded the highest 28-day value of 64.0 MPa and maintained 67.0 MPa at both 56 and 90 days. TMSM50 also showed strong later-age development, increasing from 50.5 MPa at 28 days to 64.8 MPa at 90 days. The results indicate that partial sea-sand replacement did not produce a systematic reduction in compressive strength; instead, the response

depended on the reference aggregate family and curing age. Continued strength development is consistent with the contribution of the blended binder system, particularly at later ages.

3.3 Split Tensile Strength

Table 5. Split tensile strength development (MPa)

Age (d)	TMS M100	TMS M90	TMS M50	TMS R100	TMS R90	TMS R50
28	3.14	3.15	2.99	3.11	3.12	2.83
56	3.59	3.32	3.18	3.53	3.30	3.25
90	3.65	3.40	3.28	3.60	3.38	3.46

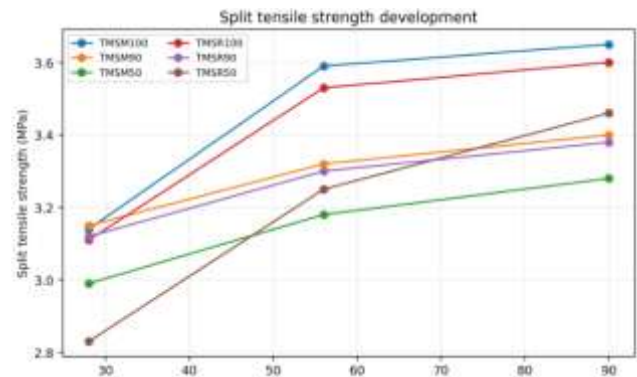


Fig. 5. Split tensile strength development with curing age.

Split tensile strength increased with curing age for all mixtures. At 28 days the values ranged from 2.83 to 3.15 MPa, while the 90-day range was 3.28–3.65 MPa. TMSM100 reached the highest 90-day split tensile strength of 3.65 MPa, followed by TMSR100 at 3.60 MPa. Although the 50% sea-sand mixtures showed lower tensile values than their corresponding controls at some ages, the differences remained within a relatively narrow range and did not indicate a general loss of indirect tensile resistance. The observed longitudinal splitting pattern is consistent with the intended failure mode of the test.

Figure 4.4: Specimens subjected to UPV, compression strength, split tensile strength, and flexural strength tests



Fig. 6. Representative post-test failure patterns: compression, split tension and flexure.

3.4 Flexural Strength

Table 6. Flexural strength development (MPa)

Age (d)	TMS M100	TMS M90	TMS M50	TMS R100	TMS R90	TMS R50
28	7.80	6.60	6.00	6.40	5.60	5.00
56	8.80	8.00	8.20	8.80	7.20	9.20
90	9.60	10.00	10.20	10.40	9.00	10.60

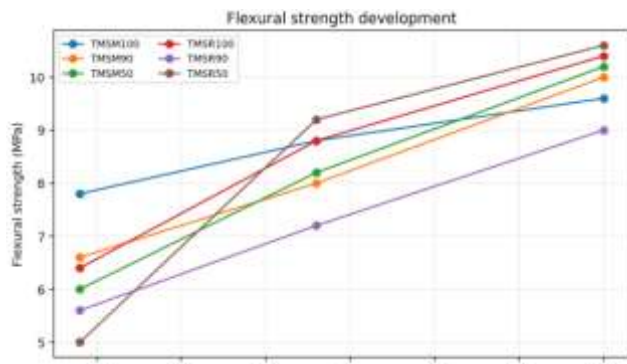


Fig. 7. Flexural strength development with curing age.

Flexural strength increased markedly with curing age in every mixture. The 28-day range was 5.0–7.8 MPa, increasing to 9.0–10.6 MPa at 90 days. TMSR50 achieved the highest 90-day flexural strength of 10.60 MPa, while TMSM50 reached 10.20 MPa. Notably, both 50% sea-sand mixtures exceeded their respective control mixtures at 90 days. The results indicate that high sea-sand replacement can remain compatible with favourable later-age bending-related material performance under the investigated conditions.

3.5 Integrated Performance Assessment

Table 7. Overall comparison of the four principal performance measures

Mix	Spr ead	Com p. 28 d	Com p. 90 d	Split 28 d	Split 90 d	Flex . 28 d	Flex . 90 d
TMS M10 0	740	53.5	64.5	3.14	3.65	7.80	9.60
TMS M90	710	51.5	60.5	3.15	3.40	6.60	10.0 0
TMS M50	700	50.5	64.8	2.99	3.28	6.00	10.2 0
TMS R10 0	690	59.0	65.5	3.11	3.60	6.40	10.4 0
TMS R90	685	57.5	62.0	3.12	3.38	5.60	9.00
TMS R50	680	64.0	67.0	2.83	3.46	5.00	10.6 0

The combined results demonstrate that no single mixture is superior in every property. TMSM100 provides the highest fresh-state spread, whereas TMSR50 provides the highest 28-day and 90-day compressive strengths and the highest 90-day flexural strength. TMSM50 also performs strongly at later ages, particularly in compressive and flexural strength. The 50% sea-sand mixtures are therefore promising candidates for further investigation because they combine substantial aggregate replacement with favourable later-age hardened performance. Their lower spread relative to the controls, however, indicates that fresh-state behaviour must be considered during mix selection.

The results also reinforce the importance of considering multiple response modes in SCC. Compressive strength alone does not describe tensile cracking or bending-related behaviour, while workability alone cannot establish hardened performance. The present results provide material-level evidence of compatibility between partial

sea-sand replacement and the selected ternary-binder SCC system; reinforced-member capacity, bond, ductility, serviceability and long-term durability require separate investigation.

4. CONCLUSIONS

The investigation evaluated six M40-grade SCC mixtures containing manufactured sand or river sand with 0%, 10% and 50% sea-sand replacement under a constant ternary binder system. The principal conclusions are:

- The ternary binder containing 65% OPC, 30% fly ash and 5% GGBS was successfully applied across the six mixtures with a total cementitious content of 590 kg/m³.
- Slump-flow spread decreased with sea-sand replacement. The manufactured-sand series decreased from 740 mm to 710 mm and 700 mm, while the river-sand series decreased from 690 mm to 685 mm and 680 mm.
- All six mixtures exceeded the 48 MPa target mean strength at 28 days, with compressive strengths of 50.5–64.0 MPa. At 90 days, TMSR50 reached 67.0 MPa and TMSM50 reached 64.8 MPa.
- Split tensile strength increased with curing age, with 90-day values between 3.28 and 3.65 MPa. No systematic adverse effect of sea-sand replacement was observed across the six mixtures.
- Flexural strength increased from 5.0–7.8 MPa at 28 days to 9.0–10.6 MPa at 90 days. TMSM50 and TMSR50 exhibited particularly strong later-age flexural performance.
- Partial sea-sand replacement is technically feasible within the investigated SCC system, provided that aggregate grading and fresh-state flow are appropriately controlled. TMSM50 and TMSR50 merit further structural validation, but a universal optimum replacement level cannot be established without durability, cost and reinforced-member data.

5. FUTURE SCOPE

Further work should validate the material response through complete laboratory records and extend the investigation to reinforced beams and slabs. Priority measurements include load–deflection response, first-crack and ultimate load, crack width, stiffness, ductility, bond behaviour and serviceability. Long-term studies under chloride, sulphate, carbonation, wet–dry and marine exposure would be necessary before broad structural durability recommendations are made. Optimization of sea-sand replacement and superplasticizer dosage, together with experimentally verified predictive models and life-cycle assessment, would further strengthen the engineering basis for sustainable SCC applications.

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