Experimental Study on Fresh and Mechanical Properties of Manufactured Sand and Recycled Aggregate Mixed Self-Compacting Concrete

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Abstract — Self-compacting concrete (SCC) offers significant construction advantages but relies on natural coarse aggregate and river sand, resources under growing environmental pressure. This study investigates the incorporation of recycled concrete aggregate (RCA) and manufactured sand (M-Sand) as partial and full replacements for these natural constituents, evaluating both fresh and hardened SCC properties. Mixes were developed with RCA and M-Sand substitution levels of 0%, 50%, and 100%, varied independently and in combination, while maintaining a constant water-to-cementitious-materials ratio. Slump flow, 28-day compressive strength, split tensile strength, and flexural strength were assessed for each mix. Results showed a consistent, monotonic decline in all properties with increasing substitution, with RCA exerting the dominant influence due to residual adhered mortar, higher porosity, and elevated water absorption, while M-Sand's effect was comparatively secondary. Despite reductions of up to 15.92% in workability, 30.21% in compressive strength, 19.45% in tensile strength, and 23.98% in flexural strength at full replacement (R100M100), all mixes satisfied EFNARC workability criteria and exceeded IS 456:2000 strength requirements for M25-grade concrete. Flexural strength proved most sensitive to combined substitution, while tensile strength remained comparatively least affected. These findings confirm that RCA and M-Sand, even at full replacement, are technically viable, sustainable alternatives to natural aggregates for standard structural-grade SCC applications, supporting waste diversion and resource conservation in concrete construction.

Keywords: Manufactured Sand, Mechanical Properties, Recycled Concrete Aggregate, Self-Compacting Concrete, Workability

I. Introduction

Concrete remains the most widely used construction material in the world, prized for its strength, durability, and adaptability, yet its production continues to place enormous pressure on natural resources through the extraction of river sand and quarried coarse aggregate. At the same time, the construction and demolition (C&D) sector generates vast quantities of waste concrete debris that are frequently disposed of in landfills rather than reused, creating a dual environmental burden of resource depletion on one side and waste accumulation on the other. Against this backdrop, the development of concrete systems that can incorporate recycled and alternative materials without compromising performance has become an important research priority, particularly for advanced concrete types such as SCC, whose mix design already departs significantly from that of conventional vibrated concrete [1-4].

SCC was first conceptualized in Japan in the late 1980s by Hajime Okamura in response to a shortage of skilled labour capable of ensuring adequate vibration and compaction, particularly in structures with congested reinforcement. The material is designed to flow under its own weight, filling formwork and encapsulating reinforcement without any external consolidation, while simultaneously maintaining resistance to segregation. Achieving this combination of filling ability, passing ability, and segregation resistance requires a fundamentally different mix proportioning strategy from that of normal concrete: a higher paste and powder content, a reduced coarse-aggregate-to-total-aggregate ratio, and the use of high-range water-reducing admixtures. Because of these proportioning differences, the hardened mechanical behaviour of SCC cannot simply be assumed to mirror that of conventional concrete of equivalent grade, a distinction that has motivated a substantial body of international research into its compressive, tensile, and flexural performance [5-6].

Parallel to this development in SCC technology, growing environmental concern has driven interest in incorporating recycled coarse aggregate (RCA), derived from demolished concrete, and manufactured sand (M-Sand), produced by crushing quarried rock, as substitutes for natural coarse aggregate and river sand respectively. RCA offers a means of diverting demolition waste from landfill while conserving virgin aggregate resources, but it is well established that residual mortar adhering to RCA particles increases porosity and water absorption while weakening the interfacial transition zone (ITZ) between aggregate and cement paste. M-Sand, meanwhile, offers a sustainable alternative to increasingly scarce and environmentally sensitive river sand mining, though its angular particle shape and higher fines content alter paste demand and packing behaviour relative to natural sand. Individually, both materials have been studied extensively in the context of conventional vibrated concrete, where moderate replacement levels have generally been shown to produce acceptable mechanical performance. However, their behaviour within the more paste-sensitive and flow-dependent environment of SCC, particularly when RCA and M-Sand are varied simultaneously across a full range of replacement levels, remains comparatively underexplored [7-8].

Existing literature on recycled-aggregate SCC has typically examined either coarse aggregate substitution or fine aggregate substitution in isolation, with relatively few studies systematically varying both materials together across the complete replacement spectrum from 0% to 100%. Moreover, much of the available research emphasizes fresh-state workability or a single mechanical property in isolation, rather than providing an integrated assessment of workability alongside compressive strength, split tensile strength, and

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flexural strength within a single controlled experimental matrix. This gap is significant because the interaction between RCA and M-Sand substitution, particularly when both act simultaneously on the ITZ and overall packing density of the mix, cannot reliably be inferred by superimposing findings from single-variable studies. A systematic investigation is therefore needed to establish whether SCC incorporating both recycled coarse aggregate and manufactured sand, even at full replacement levels, can satisfy the workability criteria established by EFNARC while still achieving mechanical performance required for standard structural-grade applications [9-10].

The present study addresses this gap by developing a series of SCC mixes in which RCA and M-Sand are varied independently and in combination across the full 0–100% replacement range, and by systematically evaluating their influence on slump flow, 28-day compressive strength, split tensile strength, and flexural strength. By examining these properties within a single, internally consistent experimental programme, the study aims to characterize both the individual and interactive effects of RCA and M-Sand on the fresh and hardened behaviour of SCC, to identify the underlying mechanisms responsible for observed performance changes, and to assess the extent to which fully substituted mixes remain viable for practical structural use. The findings are intended to contribute toward the development of sustainable SCC mix-design guidelines that support the wider adoption of recycled and manufactured constituents in structural concrete construction, while providing a clearer understanding of the trade-offs involved when both coarse and fine natural aggregates are simultaneously replaced [11-12].

II. Materials and Methodology

This study investigated the fresh and hardened properties of Self-Compacting Concrete (SCC) developed using recycled coarse aggregate (RCA) and manufactured sand (M-Sand) as partial and full replacements for natural coarse aggregate and river sand. Ordinary Portland Cement of 53-grade (IS 12269:1987) was used along with Class F fly ash (ASTM C618) as a supplementary cementitious material, incorporated in every mix to reduce cement demand and improve sustainability. Natural river sand (Zone II, IS 383-1970) and M-Sand were characterized for specific gravity, fineness modulus, bulk density, and water absorption, with M-Sand exhibiting a lower specific gravity (2.46) and slightly higher water absorption (1.2%) than natural sand. Crushed granite of 12.5 mm nominal size served as the natural coarse aggregate (specific gravity 2.58, water absorption 0.43%), while RCA, sourced from demolished building debris and processed through manual breaking and crushing, showed a lower specific gravity (2.49) and markedly higher water absorption (4.45%), reflecting residual adhered mortar. A polycarboxylate-ether-based superplasticizer (BASF Glenium 6100) was used to achieve the required flowability.

SCC mixes were proportioned by replacing natural coarse aggregate with RCA and natural sand with M-Sand independently and in combination, at 0%, 50%, and 100% replacement levels, while maintaining a constant water-to-cementitious-materials ratio of 0.36. Mix proportions were derived using a spreadsheet-based design tool that computed paste volume, mortar fraction, and aggregate quantities from the measured material properties. Mixing was carried out using a fixed sequence to ensure uniform superplasticizer dispersion and consistent fresh-state behaviour.

Fresh-state performance was assessed through the slump flow test in accordance with EFNARC guidelines, evaluating filling ability via spread diameter. Hardened properties were determined at 28 days curing: compressive strength on cubes using a compression testing machine (IS 516:1959), split tensile strength on cylinders via IS test method (IS 5816:1999), and flexural strength on prisms under two-point loading (IS 516:1959), with three specimens tested per condition and average values reported.

III. Results and Discussion

A. Workability

The slump flow results, as shown in Fig.1, revealed a consistent, monotonic reduction in workability with increasing substitution of both RCA and M-Sand, reflecting the combined influence of aggregate morphology, surface texture, and water absorption on the flowability of SCC. At 0% M-Sand, slump flow decreased from 779 mm (R0M0) to 728 mm (R50M0) to 682 mm (R100M0), a 12.45% reduction as RCA increased from 0 to 100%, attributable to residual old mortar adhering to RCA particles, which increases surface roughness, angularity, and porosity relative to natural granite aggregate. The higher water absorption of RCA reduces free water available for lubrication, while its irregular texture increases inter-particle friction, restricting spread under self-weight. Holding RCA constant while increasing M-Sand produced a comparatively smaller reduction (2.05% at R0), indicating that M-Sand's angular shape and higher fines content modestly increase paste demand without disrupting flow as severely as RCA. When both were increased simultaneously, reductions compounded, reaching a minimum of 655 mm at R100M100, a 15.92% decrease from control. Despite this cumulative reduction, all values remained within the EFNARC-specified 650–800 mm range for SCC classification, confirming that even fully substituted mixes retain adequate filling ability and self-compacting behavior. Overall, RCA exerted the dominant influence on workability loss due to inferior aggregate quality and higher absorption, while M-Sand's contribution remained secondary, governed by particle shape and fines content rather than fundamental material deficiency.

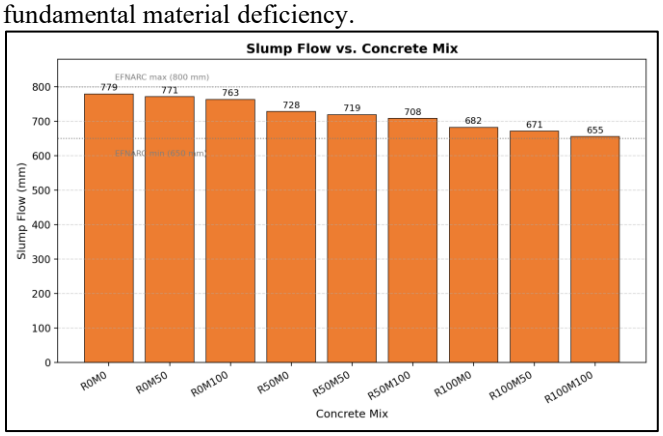

Fig. 1: Slump flow result for M sand and RCA mixed SCC

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B. Compressive Strength

The 28-day compressive strength results, as shown in Fig.2, presented a consistent, monotonic decline with increasing RCA and M-Sand substitution, reflecting the combined influence of aggregate quality and interfacial bonding on mechanical performance. At 0% M-Sand, strength decreased from 42.66 MPa (R0M0) to 36.24 MPa (R50M0) to 31.58 MPa (R100M0), a 25.97% total reduction as RCA rose from 0 to 100%. This decline is attributable to residual adhered mortar on RCA particles, which creates a weaker, more porous interfacial transition zone (ITZ) with the new cement paste, along with higher water absorption and lower particle density relative to natural granite. These factors collectively reduce load-bearing capacity and increase micro-crack propagation under compressive loading. Holding RCA constant while increasing M-Sand produced a comparatively smaller reduction — from 42.66 MPa (M0) to 39.11 MPa (M100) at R0, an 8.32% decrease — suggesting M-Sand's angular shape and higher fines content alter paste demand and packing density without compromising the aggregate-matrix bond as severely as RCA. When both substitutions acted simultaneously, effects were cumulative and interactive rather than merely additive; the lowest strength, 29.77 MPa at R100M100, represented a 30.21% reduction from control, yet remained above the 25 MPa threshold required for M25-grade concrete under IS 456:2000. This confirms that despite compounding degradation, the resulting SCC retains adequate structural viability, with RCA exerting the dominant, quality-limiting influence on strength.

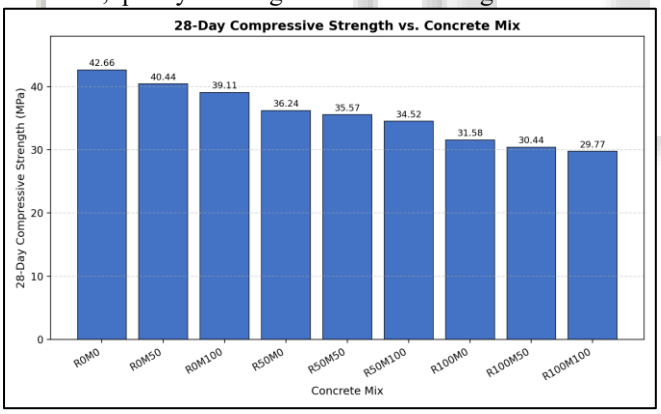

Fig. 2: Compressive strength results for M sand and RCA mixed SCC

C. Split Tensile Strength

Split tensile strength followed the same monotonic declining pattern observed for compressive strength, reflecting the governing influence of aggregate-matrix bond quality on tensile load transfer, as shown in Fig.3. At 0% M-Sand, tensile strength declined from 3.65 MPa (R0M0) to 3.38 MPa (R50M0) to 3.19 MPa (R100M0), a 12.60% reduction as RCA increased from 0 to 100%. Since tensile failure is highly sensitive to bond strength at the aggregate-paste interface, the residual mortar adhering to RCA particles creates a weaker, more porous ITZ, promoting preferential crack initiation and propagation along the aggregate boundary rather than through the aggregate itself. Holding RCA constant while increasing M-Sand produced a smaller decline — from 3.65 MPa (M0) to 3.40 MPa (M100) at R0, a 6.85% reduction — indicating that M-Sand's angular morphology and fines content influence tensile behavior less severely than RCA, though they still marginally affect paste cohesion and micro-crack resistance. When RCA and M-Sand increased simultaneously, reductions compounded, reaching a maximum of 19.45% at R100M100 (2.94 MPa) relative to control, confirming tensile strength is more sensitive to combined substitution than either variable alone. Notably, the percentage reductions in tensile strength across all combinations were consistently smaller than corresponding compressive strength losses, consistent with the expectation that tensile strength increases only with the square root of compressive strength, making it comparatively less sensitive to aggregate substitution.

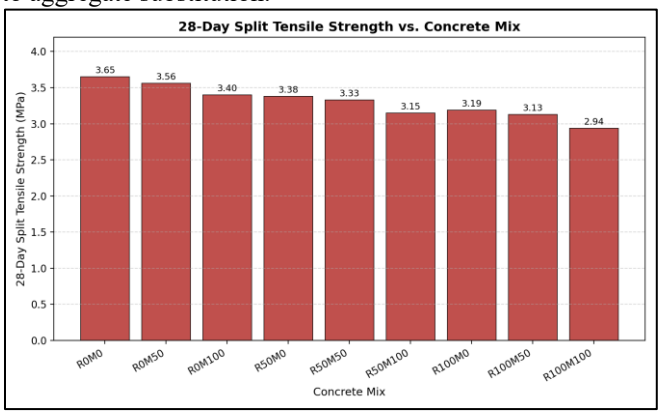

Fig. 3: Tensile strength results for M sand and RCA mixed SCC

D. Flexural Strength

Flexural strength exhibited a consistent, monotonic decline with increasing RCA and M-Sand substitution, consistent with the pattern observed for compressive and tensile strength, reflecting the pronounced sensitivity of bending resistance to interfacial bond quality within the concrete matrix, as shown in Fig.4. At 0% M-Sand, flexural strength decreased from 6.24 MPa (R0M0) to 5.65 MPa (R50M0) to 5.39 MPa (R100M0), a 13.62% reduction as RCA increased from 0 to 100%. Since flexural failure is governed primarily by tensile stresses developed at the extreme fiber of the beam, it is highly dependent on the strength of the aggregate-mortar ITZ; the residual old mortar adhering to RCA weakens this bond, creating preferential planes of weakness that promote earlier crack initiation under bending, reducing ultimate moment capacity. Holding RCA constant while increasing M-Sand produced a comparable, and slightly larger, proportional decline — from 6.24 MPa (M0) to 5.47 MPa (M100) at R0, a 12.33% reduction — indicating that M-Sand's particle shape, fines content, and altered paste-aggregate packing meaningfully influence flexural crack resistance. When RCA and M-Sand increased simultaneously, reductions compounded substantially, reaching a maximum of 23.98% at R100M100 (4.78 MPa) relative to control. This confirms flexural strength is the most sensitive of the three mechanical properties to combined substitution, since bending failure depends on the cumulative effect of multiple weak interfacial zones distributed through the beam's tension zone, with bond-dependent properties degrading disproportionately with recycled material content.

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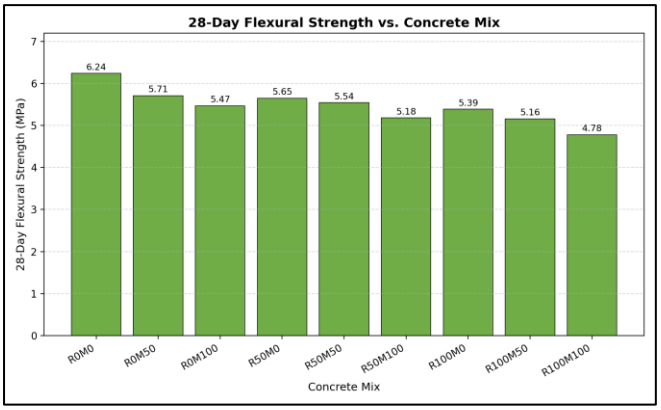

Fig. 4: Flexural strength results for M sand and RCA mixed SCC

IV. CONCLUSIONS

This study investigated the influence of recycled coarse aggregate (RCA) and manufactured sand (M-Sand) as partial and full replacements for natural coarse aggregate and river sand on the fresh and hardened properties of Self-Compacting Concrete (SCC). Based on the experimental results, several key conclusions can be drawn.

Workability decreased progressively with increasing RCA and M-Sand content, yet all mixes, including the fully substituted R100M100 combination, remained within the EFNARC-specified range of 650–800 mm, confirming that self-compacting behavior was preserved even at complete replacement. RCA exerted the dominant influence on workability loss, owing to residual adhered mortar, higher porosity, and elevated water absorption, while M-Sand's effect was comparatively secondary and governed mainly by particle angularity and fines content.

Mechanical properties followed a similar pattern of decline. Compressive strength decreased to a minimum of 29.77 MPa at R100M100, still exceeding the 25 MPa threshold required for M25-grade concrete under IS 456:2000. Split tensile strength showed a maximum reduction of 19.45%, remaining comparatively less sensitive than compressive strength due to the square-root relationship between the two properties. Flexural strength proved the most sensitive mechanical property to combined substitution, recording the highest overall reduction of 23.98%, reflecting the strong dependence of bending resistance on interfacial bond quality.

Across all properties, performance degradation was mechanistically linked to the weaker interfacial transition zone created by residual mortar on RCA and the altered particle morphology of M-Sand, with the effects of both materials proving interactive and cumulative rather than purely additive. Despite these reductions, the study demonstrates that SCC incorporating RCA and M-Sand, even at full replacement levels, satisfies EFNARC workability criteria and achieves mechanical strengths adequate for standard structural-grade applications. This establishes the technical feasibility of using these recycled and manufactured constituents as viable, sustainable alternatives to natural aggregates in self-compacting concrete construction.

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