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Investigating the Behavior of Self-Compacting Concrete Containing SCMs and Recycled Fine Aggregates

Sachin Tiwari

Research Scholar, Department of Civil Engineering, Amity School of Engineering and Technology, Amity University Madhya Pradesh, Gwalior 474020, palanikavi0109@gmail.com

Mahakavi P

Associate Professor, Department of Civil Engineering, Amity School of Engineering and Technology, Amity University Madhya Pradesh, Gwalior 474020, pmahakavi272@gmail.com

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RESEARCH ARTICLE

Investigating the Behavior of Self-Compacting Concrete Containing SCMs and Recycled Fine Aggregates

Sachin Tiwari^a, Mahakavi P^{b,*}^a Research Scholar, Department of Civil Engineering, Amity School of Engineering and Technology, Amity University Madhya Pradesh, Gwalior 474020^b Associate Professor, Department of Civil Engineering, Amity School of Engineering and Technology, Amity University Madhya Pradesh, Gwalior 474020**ABSTRACT**

This study addresses the unresolved gap in quantifying how recycled fine aggregates (RFA) and metakaolin (MK) interact synergistically in self-compacting concrete (SCC), a relationship that previous works have studied only in isolation or without mechanistic justification. Twenty-five SCC mixtures containing MK (0–25%) and RFA (0–100%) were evaluated to generate a unified understanding of fresh behaviour, strength development, pore refinement, interfacial transition zone (ITZ) characteristics, and sustainability indicators. Results show that RFA alone increases water demand and reduces strength, while MK compensates for these losses by densifying the matrix and improving ITZ bonding, as confirmed through SEM analysis. An optimum synergy was identified at 15% MK and 50% RFA, producing a 28-day strength of ≈ 47.5 MPa close to conventional SCC (≈ 50.9 MPa). Unlike previous studies focused primarily on mechanical performance, this work integrates life-cycle assessment (LCA) and life-cycle cost (LCC) analysis, demonstrating 12–13% CO₂ reduction and 6–10% cost savings. The findings establish a scientific framework that links microstructure–property relationships with sustainability performance, enabling more reliable use of high-volume RFA in SCC.

Keywords: Self compacting concrete, Metakaolin, Compressive strength, Recycled fine aggregates, Natural fine aggregates, Splitting tensile strength

1. Introduction

The growing global demand for sustainable construction materials has intensified interest in recycling construction and demolition (C&D) waste. Since C&D waste can account for 30–40% of municipal solid waste in many regions, converting it into usable aggregates is considered an effective strategy for lowering CO₂ emissions and reducing dependence on natural resources [1–4]. Considerable research has examined the use of recycled coarse (RCA) and fine aggregates (RFA) in concrete, yet the high porosity, residual mortar, and weak interfacial bonding associated with these recycled materials continue to

raise concerns regarding strength and durability [5–11,44].

To overcome these limitations, a wide range of supplementary cementitious materials (SCMs) such as silica fume, fly ash, and GGBS have been studied for their ability to refine pore structure and improve long-term durability [6–8, 42, 43, 47]. In recent years, metakaolin (MK), a highly reactive form of calcined clay has gained attention due to its strong pozzolanic activity, which enhances early-age strength, reduces permeability, and densifies the microstructure [12–14, 48]. However, research findings regarding MK's effect on fresh properties are inconsistent. Some studies report reduced flowability

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* Corresponding author.

E-mail addresses: palanikavi0109@gmail.com (S. Tiwari), pmahakavi272@gmail.com (Mahakavi P).

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due to MK's angular, ultrafine particles [14–16, 57], whereas others note improved workability for certain flash-calcined MKs with lower water demand and partially rounded morphology [17, 46, 49, 50]. These conflicting observations indicate the need for controlled experimental studies that clarify MK's influence on flow behaviour in SCC.

Research on SCC containing recycled aggregates has also produced variable results. Most studies agree that recycled aggregates negatively affect workability and strength, but the degree of deterioration differs widely. Reductions in compressive strength for SCC with 100% recycled aggregate, for instance, have been reported anywhere from 20% [18] (Corinaldesi et al., 2002) to nearly 40% [10] (Kou & Poon, 2009). Increased water demand and inconsistent durability trends spanning drying shrinkage, permeability, and chloride ingress further complicate mix-design recommendations. Although RCA has been extensively studied in SCC applications [19–21, 44] research specifically targeting SCC made with RFA remains limited, particularly regarding its interaction with highly reactive pozzolans such as MK.

Although numerous studies have examined the fresh, mechanical, and durability performance of sustainable SCC, limited research has combined experimental performance evaluation with integrated life cycle environmental and cost assessments [58–68]. Therefore, the present study not only evaluates the mechanical and microstructural performance of MK–RFA-based SCC but also incorporates cradle-to-gate life cycle assessment (LCA) and life-cycle cost (LCC) analysis to quantify its environmental and economic advantages.

1.1. Specific gaps in prior literature

Although SCC, RFA, and MK have been individually studied, several critical gaps remain. First, no previous study has systematically examined the combined behaviour of MK and RFA in SCC across multiple replacement levels, leaving their interactive effects insufficiently understood. Second, the microstructural response particularly ITZ quality, adhered mortar behaviour, and pore refinement has not been adequately investigated for SCC incorporating both MK and RFA. Third, contradictory findings on MK's influence on SCC workability persist due to variations in calcination temperature, fineness, and particle morphology, necessitating controlled experimental validation. Fourth, most existing studies focus primarily on mechanical and durability properties, while integrated life-cycle environmental and economic assessments (LCA–LCC) for MK–RFA-based SCC remain largely unexplored. Finally, an optimal

MK–RFA combination that simultaneously balances fresh performance, mechanical strength, microstructural refinement, environmental sustainability, and cost efficiency has not yet been established.

1.2. Purpose and contribution of the present study

This study aims to bridge these knowledge gaps through a comprehensive experimental evaluation of SCC incorporating five levels of MK (0–25%) and five levels of RFA (0–100%). Fresh, mechanical, and microstructural properties are examined in detail, including ITZ characteristics obtained from SEM analysis, to clarify how MK influences the performance of RFA-based SCC. In addition, an integrated life cycle assessment (LCA) and life-cycle cost analysis (LCC) are conducted to quantify the environmental and economic implications of MK–RFA incorporation. By identifying mix combinations such as 15% MK with 50% RFA that deliver strengths comparable to conventional SCC, the study provides new evidence on how reactive SCMs can offset the limitations of recycled fine aggregates. The findings contribute practical mix-design insights for producing high-performance, sustainable, and cost-effective SCC suitable for environmentally responsible construction.

2. Experimental program

2.1. Materials

2.1.1. Binders

The primary binding agents in this experimental work were Ordinary Portland Cement (OPC) of 43-grade, which complies with BIS standard IS 8112 (1959) [22], and Metakaolin, which was obtained from Jaishree Chemicals & Minerals and Mumal Microns PVT LTD, Bhopal, India. Table 1 summarizes the findings of a number of standard tests that were used to assess the mechanical and physical properties of these binders in compliance with BIS requirements and other standards. As also mentioned by Singh and Singh (2016) and Dinakar et al. (2013) [25, 26], metakaolin showed a much higher fineness (12400 cm²/g) than OPC (3200 cm²/g), supporting its filler action and ability to improve the early-age strength of concrete. The fineness of metakaolin was characterized using three complementary methods: Blaine air-permeability (IS: 4031-Part 2), laser-diffraction particle size analysis, and nitrogen adsorption (BET). Results are reported in units of cm²/g (1 cm²/g = 0.1 m²/kg). Metakaolin exhibited a significantly higher specific surface area (SSA) than Ordinary Portland Cement (OPC): Blaine fineness for OPC = 3200 cm²/g (320 m²/kg) compared to metakaolin Blaine = 12400

Table 1. Physical and mechanical properties of binders.

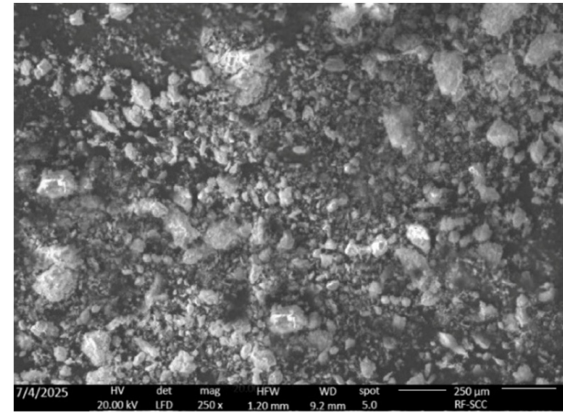
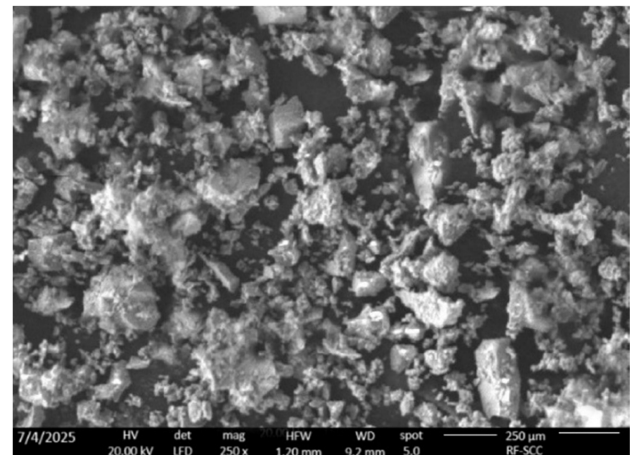
Property	Test Method	OPC	Metakaolin
Fineness	IS: 4031-Part 2 [27] Blaine air permeability (n = 3)	3200	12400
Fineness (Estimate from Particle Size Distribution)	Laser Diffraction → $D_{[3,2]}$ → Specific Surface Area (Malvern Mastersizer; wet dispersion, dispersant, sonication 30 s; Refractive Index = 1.58) (n = 3)	—	12200
Specific Surface Area	ISO 13320:2009 [23] BET (N_2 adsorption; degas 110 °C, 12 h) (Micromeritics 2020) (n = 3)	—	18240
Consistency (%)	ISO 9277:2010 [24] IS: 4031 (Part 4) – 1988 [28]	33	—
Initial Setting Time (min)	IS: 4031 (Part 5) – 1988 [29]	66	—
Final Setting Time (min)		274	—
Specific gravity	IS: 4031 (Part 11) – 1988 [31]	3.14	2.68
Mortar Strength (MPa) 7 Days	IS: 4031 (Part 6) – 1988 [30]	33.73	—
Mortar Strength (MPa) 28 Days		46.73	—
pH	—	—	6.6

cm^2/g ($1240 \text{ m}^2/\text{kg}$). Laser-diffraction measurements ($D_{[3,2]}$ converted to SSA, assuming spherical geometry and a particle density of $\rho = 2600 \text{ kg/m}^3$) yielded an estimated SSA of $12,200 \text{ cm}^2/\text{g}$, while BET measurements provided a value of $18,000 \text{ cm}^2/\text{g}$. The higher BET value reflects adsorption to particle surfaces, including surface roughness and internal porosity, which are not fully captured by optical scattering (laser) or air-permeability (Blaine) methods. For clarity, the results are provided from each method separately, rather than using a simple arithmetic average. The mean values (n = 3) for each method are provided in Table 1. For engineering comparisons with cement fineness standards, the Blaine value is referenced, while BET is used as the primary indicator of chemical surface area relevant to pozzolanic reactivity.

Scanning electron microscopy, or SEM, was used to learn more about the morphology of these materials. Figs. 1 and 2 display the SEM pictures of OPC and metakaolin, respectively. In contrast to metakaolin, which has irregular particle forms and similarly rough surfaces, OPC particles appear angular and rough in texture based on the micrographs. The pictures clearly show that the metakaolin particles are much finer than the OPC particles.

Energy Dispersive Spectroscopy (EDS) was also carried out; the corresponding spectra are shown in Fig. 3 (OPC) and Fig. 4 (flash calcined Metakaolin MK). Carbon (C), oxygen (O), silicon (Si), and calcium (Ca) were identified as the main elements in the EDS investigation of OPC. On the other hand, metakaolin displayed components like iron (Fe), silicon (Si), potassium (K), titanium (Ti), and aluminum (Al) in greater amounts. Table 2(a) provides specifics on these elements' weight percentages.

To determine the phases and crystalline nature of the chemicals found in both OPC and metakaolin,

**Fig. 1.** SEM micrographs of OPC.**Fig. 2.** SEM micrographs of metakaolin.

X-ray diffraction (XRD) examination was also carried out. The OPC sample's crystalline character is demonstrated by the strong peaks in the XRD patterns, which are displayed in Figs. 5 and 6, respectively.

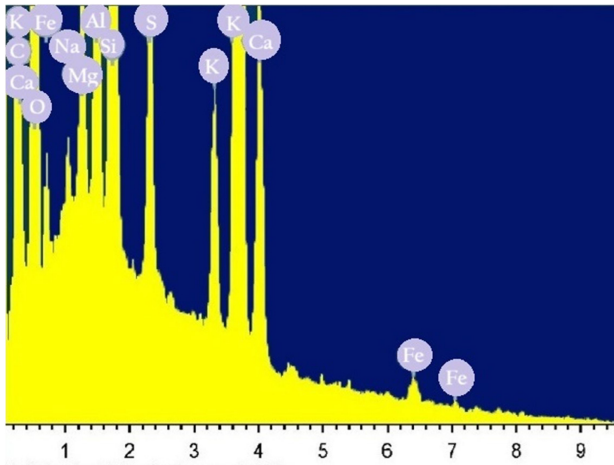


Fig. 3. EDS spectrum of OPC.

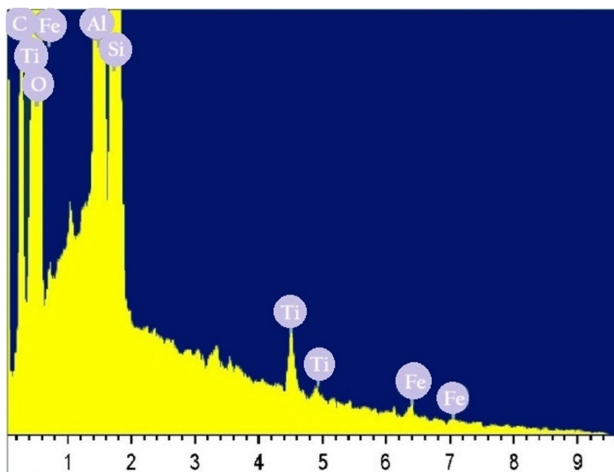


Fig. 4. EDS spectrum of metakaolin.

Table 2(a). Chemical composition (weight %) of elements in OPC and metakaolin.

Element Symbol	Chemical Name	OPC (%)	Metakaolin (%)
O	Oxygen	66.54	71.05
C	Carbon	16.25	9.20
Ca	Calcium	11.60	0.00
Si	Silicon	5.51	12.45
Al	Aluminium	1.89	11.93
S	Sulphur	1.02	0.00
Mg	Magnesium	0.81	0.00
K	Potassium	0.79	0.00
Na	Sodium	0.33	0.00
Fe	Iron	0.24	0.08
Ti	Titanium	0.00	0.28

Along with minor phases like gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and tricalcium aluminate (C_3A), the principal phases found in OPC are belite and alite, which are essential for strength growth. In the meantime, peaks that correspond to crystalline minerals such as quartz,

kaolinite, illite, muscovite, and anatase can be seen in the XRD pattern of metakaolin. The presence of silica and alumina, two amorphous phases that are important contributors to the material's pozzolanic reactivity [51], is indicated by a broad halo between 17° and 30° .

Table 2(b) lists the chemical compositions of both binders. With levels of 53.56% and 41.5%, respectively, of silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), metakaolin was found to be richer than OPC (20.46% and 5.83%). This mixture emphasizes the potent pozzolanic properties of metakaolin. However, it lacks the capacity to hydrate on its own because of its extremely low calcium oxide (CaO) content (0.03% as opposed to 64.2% in OPC). The results of the EDS study were supported by the detection of trace amounts of TiO_2 (1.54%) and FeO_3 (1.38%). Additionally, metakaolin's chemical profile meets IS 16354 (2015) [45] requirements: the total of FeO_3 and TiO_2 is less than 3% (actual: 2.92%), the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio is 1.29 (above the minimum 1.15), and the combined SiO_2 and Al_2O_3 content surpasses 94% (actual: 95.06%). The high grade of metakaolin utilized in this study is confirmed by the alumina content, which at 41.5% also surpasses the necessary 40%.

In this experiment, recycled fine aggregates (RFA) were produced by crushing **concrete waste** from **laboratory-prepared concrete cubes**. These cubes, which were cast, tested, and discarded in the lab, were taken to an external location (industry) and crushed using an impact crusher to produce the recycled aggregates. Two major issues were addressed by this strategy. First, by utilizing a single supply of concrete, the recycled aggregates were guaranteed to be consistent, reducing the unpredictability that is sometimes seen when materials are supplied from several locations. Second, because the initial concrete mix's composition and characteristics were well-established, having complete control over it made it possible to comprehend and interpret the results more clearly. Table 3 lists the Composition of Control Mix for Self-Compacting Concrete (SCC). The concrete was crushed into aggregates with sizes ranging from 0 to 38.1 mm after 35 days of cure. To match the maximum size of the fine natural aggregates (river sand) utilized in comparison, only particles smaller than 1.19 mm were chosen for this study. The particle size distributions (grading curves) of the recycled and natural aggregates showed significant variations after this screening procedure. The grading curve of the recycled aggregates was changed to resemble that of the natural sand in order to guarantee that all concrete mixes had a constant fineness modulus.

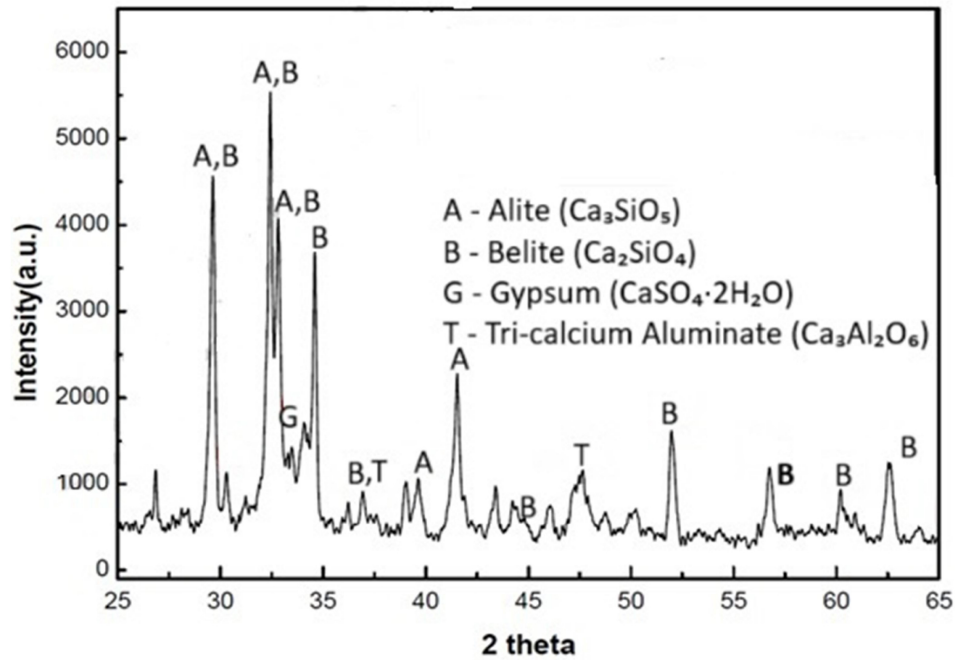


Fig. 5. XRD pattern of OPC.

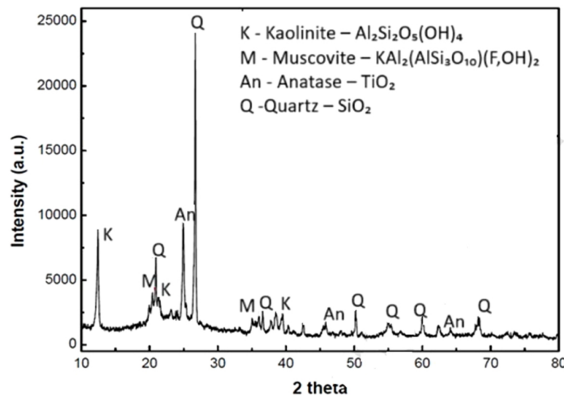


Fig. 6. XRD pattern of metakaolin.

Table 2(b). Chemical composition of metakaolin and OPC.

Component	Metakaolin (%)	OPC (%)
SiO ₂ (Silicon Dioxide)	53.56	20.46
Al ₂ O ₃ (Aluminum Oxide)	41.50	5.83
CaO (Calcium Oxide)	0.03	64.2
TiO ₂ (Titanium Dioxide)	1.54	—
Fe ₂ O ₃ (Iron Oxide)	1.38	—
MgO (Magnesium Oxide)	—	3.5
SO ₃ (Sulfur Trioxide)	—	3.1
K ₂ O (Potassium Oxide)	—	0.75
Na ₂ O (Sodium Oxide)	—	0.5
Loss on Ignition (LOI)	—	2.2
SiO ₂ (Silicon Dioxide)	53.56	20.46
Al ₂ O ₃ (Aluminum Oxide)	41.50	5.83
CaO (Calcium Oxide)	0.03	64.2
TiO ₂ (Titanium Dioxide)	1.54	—
Fe ₂ O ₃ (Iron Oxide)	1.38	—

The recycled aggregates were meticulously sieved into particular size fractions in order to accomplish this. To maintain their condition for mixing, these fractions were kept apart in airtight containers to stop any moisture exchange with the outside world. This approach was used in this work to reduce variability and isolate the impact of aggregate replacement on the outcomes, despite the fact that it was fairly labor-intensive and unfeasible for large-scale applications. This degree of control made it possible for a more precise and significant analysis by lowering experimental noise.

It was crucial to first assess the characteristics of the aggregates utilized, especially the fine particles, in order to ascertain the composition of the various concrete mixes. The main differences between recycled fine aggregates (RFA) and natural fine aggregates (NF) are shown in Table 4. Because of their larger porosity, the recycled aggregates often had lower specific gravities than their natural equivalents. The regenerated aggregates absorbed more water as a result of the enhanced porosity. A polycarboxylic-ether based admixture, marketed under the name Glenium Master Sky 8233, was utilized as the super plasticizer. Concrete was mixed and cured using potable water.

2.2. Mix proportioning

In compliance with EFNARC requirements, the mix proportions for Self-Compacting Concrete (SCC) were

Table 3. Composition of control mix for self-compacting concrete (SCC).

Materials / Properties	Control SCC Mix
Cement (kg/m ³)	436
Natural fine Aggregate / River Sand (kg/m ³)	919
Coarse Aggregate (kg/m ³)	1097
Water (l/m ³)	184
Water-binder Ratio (W/b)	0.42
SP Dosage	7.8
Slump flow Diameter (mm) – J ring Test	750

Table 4. Properties of recycled fine aggregates (RFA) and natural fine aggregates (NF).

Properties	RF	NF
Dry specific density (kg/m ³)	2066	2747
Surface dry specific density (kg/m ³)	2338	2769
Dry bulk density (kg/m ³)	1332	1638
Water absorption (%)	14.15	0.86
Finess modulus	2.57	2.57

created. Five different replacement levels of recycled fine aggregates (RFA) were used in this study to partially replace natural fine aggregates (NCA): 0%, 25%, 50%, 75%, and 100% by weight. At the same time, 10%, 15%, 20%, and 25% replacement levels of metakaolin (MK) were used to replace cement in the mix, with the aim of enhancing its strength and durability. As advised by EFNARC, the fresh concrete qualities of all SCC mixes were assessed, including flowability and passing ability tests. [Table 5](#) provides the specific mix proportions for each combination.

2.3. Life cycle cost analysis (LCC) procedure

Life-cycle cost analysis was carried out by considering material costs, construction costs, and maintenance costs. Unit material prices were obtained from standard Indian construction cost data relevant to Madhya Pradesh. Reduced maintenance requirements due to MK incorporation were also taken into account. The same three representative mixes selected for LCA were used for LCC evaluation.

2.4. Performance evaluation and optimization

The results obtained from fresh, mechanical, microstructural, environmental, and economic assessments were collectively analyzed to identify the optimum MK–RFA combination. The selection of the best-performing mix was based on achieving a balance between strength performance, durability enhancement, CO₂ emission reduction, and life-cycle cost efficiency.

3. Methodology

The SCC mixes were made by first blending dry ingredients such as cement, metakaolin, fine and coarse aggregate for approximately one minute. To guarantee a uniform mixture, water and a superplasticizer were added after the initial mixing, and mixing was continued for a further three to four minutes. Natural fine aggregates (NF) were substituted with recycled fine aggregates (RFA) at weight percentages of 25%, 50%, 75%, and 100%. Similarly, 10%, 15%, 20%, and 25% of the metakaolin was substituted with cement. A number of conventional experiments, such as the slump flow test, V-funnel test, L-box test, and J-ring test, were carried out in accordance with EFNARC protocols in order to evaluate the new properties of SCC.

Prisms, cylinders, and cubes were produced as specimens for evaluating hardened concrete. These were demolded and sent to a curing tank for water curing after being in steel molds for a whole day. A digital compression testing machine with a 3000 kN capacity was used to measure compressive strength and split tensile strength, and a 100 kN capacity machine with a two-point loading arrangement was used to evaluate flexural strength. A naming scheme was employed to make the mixtures easily identifiable: “RF” stands for the percentage of recycled fine aggregate, and “MK” for the percentage of Metakaolin. For example, the mixture with the label MK10RF25 contains 10% metakaolin and 25% RF.

The compressive strength of 100 mm × 100 mm × 100 mm cube specimens was determined at curing ages of 7 and 28 days. Splitting tensile strength was evaluated using cylindrical specimens with a diameter of 100 mm and a height of 200 mm. Flexural strength was measured on prism specimens of 100 mm × 100 mm × 500 mm using a three-point bending configuration. All mechanical tests were performed in accordance with IS 516:2021 standards [32].

4. Results and discussion

4.1. Fresh properties

The fresh characteristics of all SCC mixes that included metakaolin (MK) and recycled fine aggregate (RFA) were evaluated in compliance with European Federation of National Associations Representing for Concrete (Self-Compacting Concrete Guidelines – EFNARC) guidelines [34] ([Table 6](#)). Satisfactory flowability was shown by slump flow diameters ranging from 675 mm to 750 mm, which is within the 650–800 mm range defined by the EFNARC. The EFNARC criteria of ≥ 0.80 is met by LL-box ra-

Table 5. Proportions of self-compacting concrete mixes (kg/m³).

Mix Type	Cement	NF	RFA	Natural Coarse Aggregate	MK	Water	SP Dosage
CM	436	919	–	1097	–	184	7.8
RF25	436	689.25	229.75	1097	–	184	7.8
RF50	436	459.5	459.5	1097	–	184	7.8
RF75	436	229.75	689.25	1097	–	184	7.8
RF100	436	0	919	1097	–	184	7.8
MK10	392.4	919	–	1097	43.6	184	7.8
MK15	370.6	919	–	1097	65.4	184	7.8
MK20	348.8	919	–	1097	87.2	184	7.8
MK25	327	919	–	1097	109	184	7.8
MK10RF25	392.4	689.25	229.75	1097	43.6	184	7.8
MK10RF50	392.4	459.5	459.5	1097	43.6	184	7.8
MK10RF75	392.4	229.75	689.25	1097	43.6	184	7.8
MK10RF100	392.4	0	919	1097	43.6	184	7.8
MK15RF25	370.6	689.25	229.75	1097	65.4	184	7.8
MK15RF50	370.6	459.5	459.5	1097	65.4	184	7.8
MK15RF75	370.6	229.75	689.25	1097	65.4	184	7.8
MK15RF100	370.6	0	919	1097	65.4	184	7.8
MK20RF25	348.8	689.25	229.75	1097	87.2	184	7.8
MK20RF50	348.8	459.5	459.5	1097	87.2	184	7.8
MK20RF75	348.8	229.75	689.25	1097	87.2	184	7.8
MK20RF100	348.8	0	919	1097	87.2	184	7.8
MK25RF25	327	689.25	229.75	1097	109	184	7.8
MK25RF50	327	459.5	459.5	1097	109	184	7.8
MK25RF75	327	229.75	689.25	1097	109	184	7.8
MK25RF100	327	0	919	1097	109	184	7.8

tios (H_2/H_1) between 0.80 and 0.91, indicating that the mixes generally have acceptable passage ability. Mixtures ranging from MK25RF25 to MK25RF100, however, only demonstrated sufficient passing capacity; blockage was occasionally seen during flow. All U-box values (7.8–9.9 mm) fall within the permitted range of EFNARC (≤ 30 mm), suggesting that all mixes have satisfactory filling capabilities.

Although metakaolin (MK) possesses a significantly higher specific surface area than ordinary Portland cement, its incorporation up to 15% resulted in an increase in slump flow and improved passing ability of SCC mixes under a constant superplasticizer dosage. This behavior can be attributed to the physical characteristics of the flash-calcined metakaolin used in this study. Unlike conventional highly angular MK, the particles exhibit partially rounded morphology and a relatively smooth surface texture, which produces a micro-ball-bearing effect that enhances particle lubrication within the cementitious matrix. In addition, the ultrafine MK particles act as fillers that occupy the voids between cement grains, improving particle packing density and reducing internal friction during flow. This filler-induced densification minimizes inter-particle resistance and facilitates easier movement of the paste, thereby enhancing the overall flowability of SCC. At higher replacement levels beyond 15%, the excessive surface area of MK increases water demand and paste viscosity, which leads to a

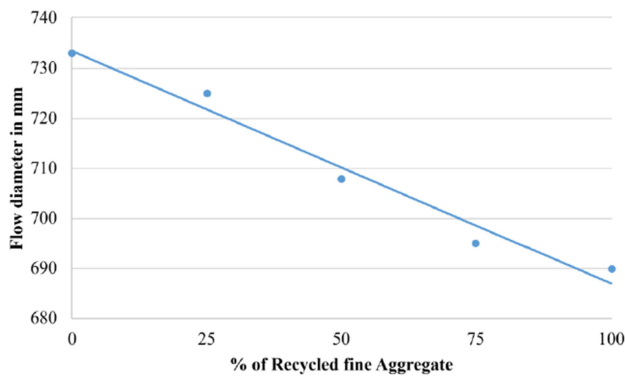
gradual reduction in flow performance despite the constant superplasticizer content. Similar trends have been reported for flash-calcined MK in SCC by San Nicolas et al. (2013, 2014) and Meddah et al. (2018) [16, 17].

4.1.1. Effect of recycled fine aggregate on flow diameter and flow time

The impact of different RFA contents on slump flow diameter and T50cm duration is shown in Fig. 7 and 8. Fig. 7 illustrates how the flow diameter shrank as the RFA content rose. Because recycled aggregates are more heterogeneous than native aggregates and have higher porosity, rough texture, and irregular form, this reduction can be explained. Because of the higher water consumption and internal friction, these characteristics make the concrete less flowable. All mixes with RFA between 733 mm and 690 mm nevertheless met EFNARC's flowability requirements for SCC in spite of the decline. With values ranging from 3.08 seconds to 4.60 seconds, Fig. 9(a) illustrates a small rise in the T50cm time as the proportion of RFA rose. Because of the microcracks in the recycled particles and the weakly adhering mortar, RFA can lower the workability of concrete. Although RFA reduces the workability of concrete, this effect can be lessened. For instance, it is well known that concrete performs better when ordinary Portland cement (OPC) is substituted with supplementary cementing

Table 6. Rheological properties of fresh SCC mixes.

Mix Type	J-Ring (mm)	Df (H ₂ -H ₁) (mm)	L-Box (H ₂ /H ₁)
CM	750	8.3	0.84
RF25	740	8.6	0.83
RF50	720	8.8	0.81
RF75	700	9.2	0.79
RF100	680	9.8	0.76
MK10	730	8.4	0.85
MK15	735	8.2	0.87
MK20	740	8	0.89
MK25	745	7.8	0.91
MK10RF25	735	8.3	0.86
MK10RF50	740	8.2	0.87
MK10RF75	745	8	0.88
MK10RF100	750	7.9	0.89
MK15RF25	738	8.2	0.87
MK15RF50	735	8.3	0.86
MK15RF75	732	8.4	0.86
MK15RF100	730	8.5	0.85
MK20RF25	728	8.5	0.84
MK20RF50	725	8.6	0.83
MK20RF75	722	8.8	0.82
MK20RF100	720	8.9	0.8
MK25RF25	720	9.5	0.8
MK25RF50	705	10.2	0.78
MK25RF75	690	10.8	0.75
MK25RF100	675	11.3	0.72

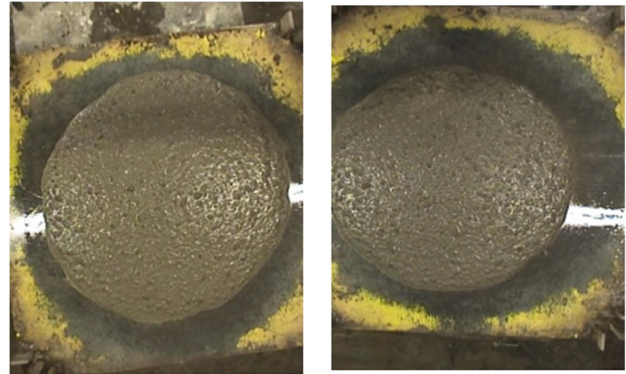
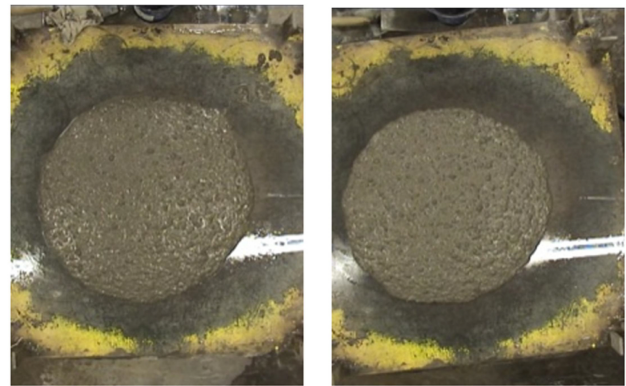
**Fig. 7.** Flow diameter of SCC made with RFA mixes

materials (SCM), such as fly ash, metakaolin, or blast furnace slag [35].

Figs. 8(a) and 8(b) present the surface appearance and flow spread of Control SCC mixes and 15% MK with 50% RFA. The images highlight the visible differences in cohesiveness and spread diameter as the recycled fine aggregate content increases.

4.1.2. Effect of metakaolin on flow diameter and flow time

The effect of replacing Metakaolin (MK) on slump flow diameter and T50cm flow duration is shown in Figs. 9(b) and 9(c). Fig. 9(b) illustrates how the slump flow diameter, which ranges from 762 mm to

**Fig. 8(a).** Flow diameter of control SCC made**Fig. 8(b).** Flow diameter of SCC made with 15% MK + 50% RFA mixture replacement

790 mm, steadily increases as the MK content rises. Metakaolin, on the other hand, efficiently fills in the matrix's gaps and lowers the mixture's overall cohesiveness, which affects flowability. When MK was added, the T50cm time dropped in Fig. 9(c), falling between 4.50 and 3.20 seconds. As stated by Benli et al. (2024) [37], this decrease indicates a rise in the flow rate because of the small and dense structure of FS particles, which lower resistance inside the matrix. Consequently, the viscosity and flow of all MK-modified mixtures were within acceptable SCC ranges.

4.1.3. Combined effect of recycled fine aggregate (RFA) and metakaolin (MK) on flow properties

The slump flow diameter fluctuation of self-compacting concrete (SCC) mixes containing varying percentages of Metakaolin (MK) (10%, 15%, 20%, and 25%) in conjunction with recycled fine aggregate (RFA) is depicted in Fig. 9(d). All RFA levels showed a steady decrease in flow diameter as the MK content rose. For 10% MK, the flow was between 730 and 690 mm, for 15% MK, it was between 735 and 695 mm, for 20% MK, it was between 740 and 700 mm,

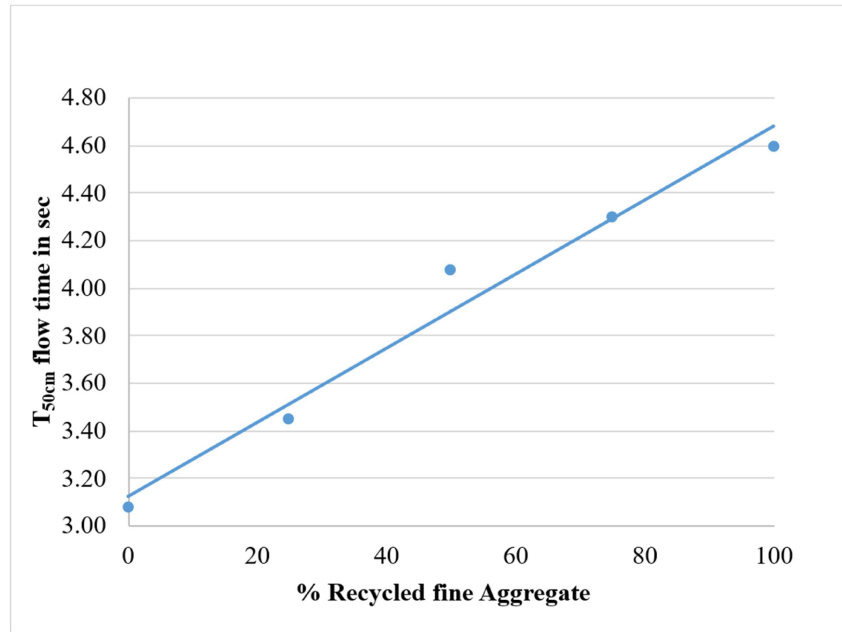


Fig. 9(a). T50cm flow time of SCC made with RFA mixes

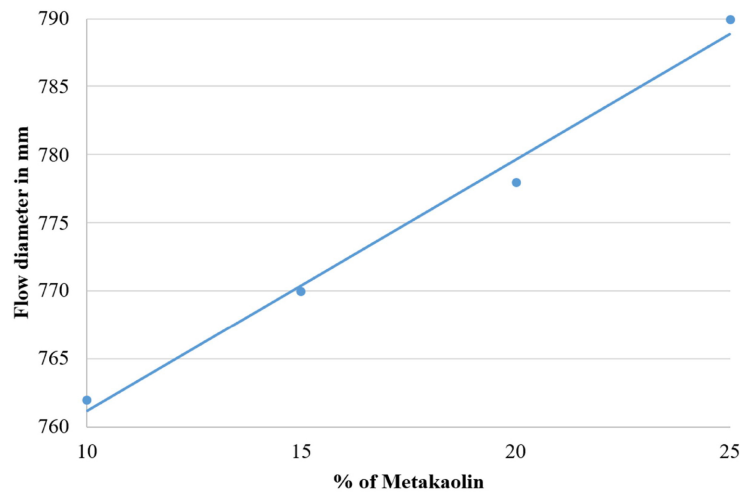


Fig. 9(b). Flow diameter of SCC mixes made with metakaolin

and for 25% MK, it was between 741 and 705 mm. The combined impact of FS's denser particle structure and RCA's porous character, which lower the concrete mix's overall workability, is responsible for this downward tendency.

4.1.4. V-funnel test results

Self-compacting concrete's (SCC) viscosity and filling capacity are evaluated using the V-Funnel test. Recycled fine aggregate (RFA)-containing mixtures in the current investigation showed a steady increase in flow time, from 8.6 to 9.8 seconds as the RFA concentration rose from 25% to 100%. This pattern suggests that RFA has a detrimental effect on SCC's workabil-

ity, mostly because of its angular texture, increased water absorption, and fine particle content, which raise the mix's viscosity and hinder its free flow. However, the flow properties were positively impacted by the addition of metakaolin (MK). The V-Funnel time improved from 8.4 to 7.8 seconds as the MK content rose from 10% to 25%, suggesting improved workability. MK effectively counteracts this effect to an extent, thereby enhancing the overall performance of SCC in terms of filling ability and viscosity. MK's pozzolanic activity and micro-filler effect, which aid in improving the mix's cohesiveness and fluidity while also fine-tuning the pore structure, are responsible for this improvement. The results showed a balanced

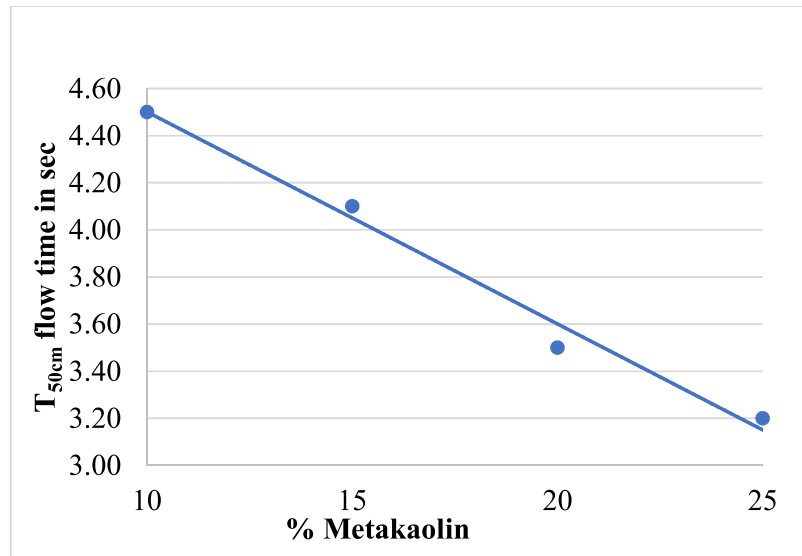


Fig. 9(c). T50cm flow time of SCC mixes made with metakaolin

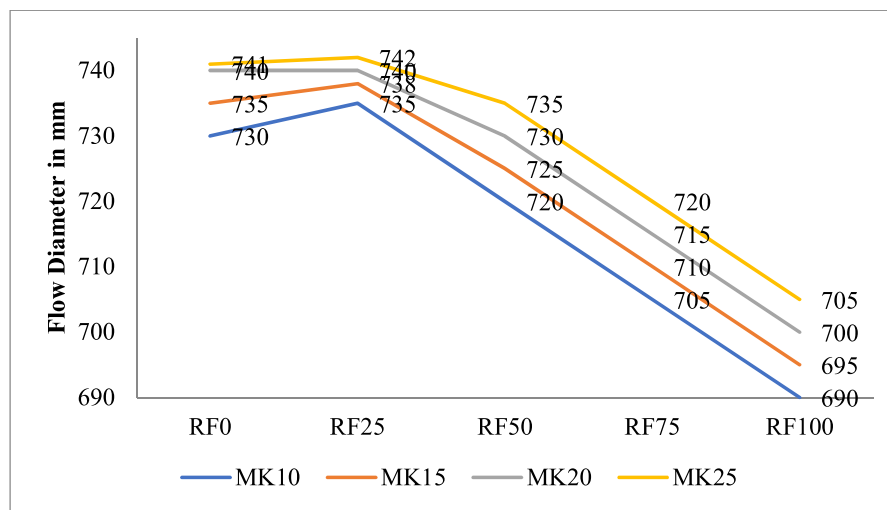


Fig. 9(d). Flow diameter of RF-SCC mixes with metakaolin.

interaction when RFA and MK were mixed. The inclusion of MK considerably lessened the negative effect, even though increasing the RFA level in these blended mixes still resulted in longer flow durations. For instance, the flow times varied between 8.3 and 7.9 seconds in the mixes containing 10% MK and between 9.5 and 11.3 seconds in the mixtures containing 25% MK.

4.1.5. J-ring test results

The J-Ring test assesses self-compacting concrete's (SCC) ability to pass, specifically its ability to flow through obstructed areas and replicate crowded reinforcing. The control mix (CM), which had a ring flow diameter of 750 mm, demonstrated the best

passing ability. J-Ring values consistently decreased from 740 mm (RF25) to 680 mm (RF100) as the amount of recycled fine aggregate (RFA) increased, demonstrating the detrimental impact of RFA on flowability. Because of its uneven shape and rough surface texture, RFA probably increases internal friction and obstructs movement. Conversely, the J-Ring flow was enhanced by the addition of metakaolin (MK), with values rising from 730 mm at 10% MK to 745 mm at 25% MK. MK's micro-filling and dispersing properties [53, 54], which improve cohesiveness and lower inter-particle friction, are responsible for this improvement. When MK and RFA were combined, the positive effects of MK somewhat outweighed the detrimental effects of RFA. While greater MK mixes with rising RFA still performed better than RFA-only

mixes, the mix with 10% MK and 100% RFA, for example, maintained a high J-Ring value of 750 mm, comparable to the control mix. This suggests that even when performance-limiting fine recycled aggregates are present, MK successfully improves SCC's passing capacity.

4.1.6. L-box test results

The L-Box test calculates the ratio of the concrete height at the end of the horizontal section to the vertical section (H_2/H_1) in order to assess the passing ability and flow uniformity of SCC. A greater ratio (nearer 1.0) indicates less blockage and better flow. A excellent ratio of 0.84 was displayed by the control mix, which progressively dropped from 0.83 (RF25) to 0.76 (RF100) as the RFA level increased. This pattern supports the detrimental effects of RFA on flowability and passing ability, which are probably caused by the angularity of the particles and the low packing density, which prevent the concrete from moving smoothly through the L-Box. In contrast, the L-Box ratio improved from 0.85 (MK10) to 0.91 (MK25) as a result of metakaolin. This improvement results from MK's contribution to paste volume, segregation resistance, and mix matrix refinement. The L-Box data indicated that MK lessened the obstructive effect of RFA in mixes that contained both MK and RFA. For instance, the MK10RF100 mix outperformed the RF100 mix alone with a ratio of 0.89. Nevertheless, the ratio decreased to 0.72 at the maximum MK and RFA combination (MK25RF100), suggesting that too much RFA content can negate the positive benefits of MK. Overall, the L-Box results show that MK increases passing ability while RFA tends to decrease it, and that using both at the same time calls for a balanced strategy to preserve the best SCC performance.

4.1.7. Explanation of workability increase at higher metakaolin replacement levels

The slump and spread results presented earlier show that all mixtures met the required workability targets. This outcome differs from many previous studies on SCC containing conventionally calcined metakaolin [46, 47, 49], where MK additions typically needed to remain below 15% to maintain flowability. In contrast, the present work achieved satisfactory workability even at a 25% cement replacement using flash-calcined MK by making minor adjustments to the superplasticizer dosage. This improved behaviour is closely linked to the particle characteristics produced by flash-calcination. Earlier investigations [39, 50] indicate that the rapid thermal treatment disrupts the layered structure of natural kaolinite and produces a fraction of nearly spherical particles ($\approx 10\text{--}15\%$), which are not normally found

in MK generated through slower or rotary kiln calcination. Additionally, the MKF used in this study contains a higher quartz fraction (Fig. 3), which, according to prior reports [51–53], is associated with lower water demand than highly pure metakaolin. These features together appear to reduce the overall water requirement, contributing to the enhanced fresh properties observed.

To maintain favourable paste flow at elevated MK replacement levels—without undue dependence on superplasticizers—a constant water-to-binder ratio of 0.42 was selected. Although the fineness of MK is generally expected to increase water demand, the current findings show improved workability at higher replacement levels due to several combined effects:

- **Pozzolanic activity leading to lower free-water demand:** The rapid reaction between MK and portlandite forms additional C–S–H gel, which refines the microstructure and moderates inter-particle friction. This can reduce the amount of free water needed to maintain lubrication, thereby improving flow [46, 47].
- **Enhanced packing density:** The fine MK particles occupy void spaces between larger cement grains, creating a denser granular arrangement. This optimisation of particle packing reduces internal resistance and facilitates smoother deformation during flow [39, 50].
- **Reduced early stiffening due to lower clinker content:** Higher MK percentages decrease the cement fraction, lowering hydration heat and slowing early structure formation. This delayed stiffening supports improved workability in the fresh state [51].
- **Favourable interaction with superplasticizer:** Even with a constant SP dosage, the adsorption of dispersant molecules onto the high-surface-area MK particles enhances particle separation. Improved dispersion lowers mixture viscosity and contributes to the observed workability gains at elevated MK levels.

4.2. Mechanical properties

A number of laboratory tests were used to assess the concrete's mechanical performance, including its split tensile, flexural, and compressive strengths. The findings are given here, along with graphical interpretations. **Compressive strength tests** were carried out using a 2000 kN capacity universal compression testing machine (CTM), where cubic or cylindrical specimens were loaded axially until failure, and the maximum load was recorded. **Splitting tensile strength tests** were also performed on cylindrical

specimens using the same CTM, with steel packing strips placed along the loading diameter to ensure uniform stress distribution. **Flexural strength tests** were conducted on prism specimens using a calibrated flexural testing frame under a two-point loading arrangement, with the load applied gradually until the specimen fractured, and the ultimate flexural stress was recorded. Figs. 10(a) to 10(c) shows the typical failure patterns of concrete specimens under compressive, splitting tensile, and flexural loading. Cubes exhibited edge crushing and vertical cracking, cylinders showed longitudinal splitting, and prisms developed a single dominant mid-span flexural crack.



Fig. 10(a). Failure patterns of test specimens after compressive strength testing: Cube specimens showing typical vertical cracking and crushing at the edges.



Fig. 10(b). Failure patterns of test specimens under axial compression: Cylindrical specimens exhibiting longitudinal splitting and shear-type failure.



Fig. 10(c). Failure patterns of test specimens under flexural loading: Prism specimens exhibiting a single dominant vertical crack.

4.2.1. Compressive strength

4.2.1.1. Influence of MK on compressive strength.

Fig. 11 shows how SCC's compressive strength developed at 7 and 28 days with different percentages of metakaolin (MK). Strength was greatly increased to an ideal level with the addition of MK [55, 56]. In comparison to the control mix (CM, 40.6 MPa), the compressive strength of the mixes containing 10%, 15%, and 20% MK rose by 6.65%, 14.53%, and 8.62% at 7 days, respectively. Strength gains over the control (50.9 MPa) at 28 days were 6.67% (MK10), 16.12% (MK15), and 8.99% (MK20). At 15% MK (59.1 MPa), the maximum strength was measured, indicating increased matrix densification and pozzolanic activity. However, as reported by Asghari et al. (2023) [36], the cement was diluted by excessive replenishment, which is probably why the compressive strength decreased by 14.29% after 7 days and 13.17% at 28 days at 25% MK.

4.2.1.2. Influence of recycled fine aggregate on compressive strength.

The compressive strength of SCC mixes with different proportions of recycled fine aggregate (RFA) is depicted in the Fig. 12. At 7 and 28 days, the control mix (CM) reached 40.6 and 50.9 MPa, respectively. There was a noticeable decrease in compressive strength as the RFA content rose. Comparing RF25, RF50, RF75, and RF100 to CM at 7 days, the strength decreased by roughly 6.4%, 21.7%, 35.2%, and 49.5%, respectively. Likewise, the decreases were around 7.9%, 16.5%, 32.8%, and 45.4% at 28 days. The strength and integrity of the hardened concrete matrix are compromised by the increased porosity, lower density, and poor interfacial bonding of recycled fine aggregates, which frequently contain microcracks and leftover mortar.

4.2.1.3. Combined effect of recycled fine aggregate and metakaolin on RF-SCC.

The compressive strength of self-compacting concrete (SCC) mixes with different proportions of metakaolin (MK) and recycled fine aggregate (RFA) at various curing ages (7 and 28 days) is shown in the Fig. 13. The control mix with no replacement shows the maximum strength, with compressive values of 40.6 MPa after 7 days and 50.9 MPa after 28 days. When RFA is used alone, compressive strength significantly decreases in comparison to the control mix. Because of the weaker binding and increased porosity of recycled aggregates, increasing RFA content has a negative impact on strength, since this declining tendency is consistent over all MK levels. However, the addition of MK improves the compressive strength. The dilution effect appears to take over beyond 15%, decreasing the amount of calcium hydroxide available for reaction and strength.

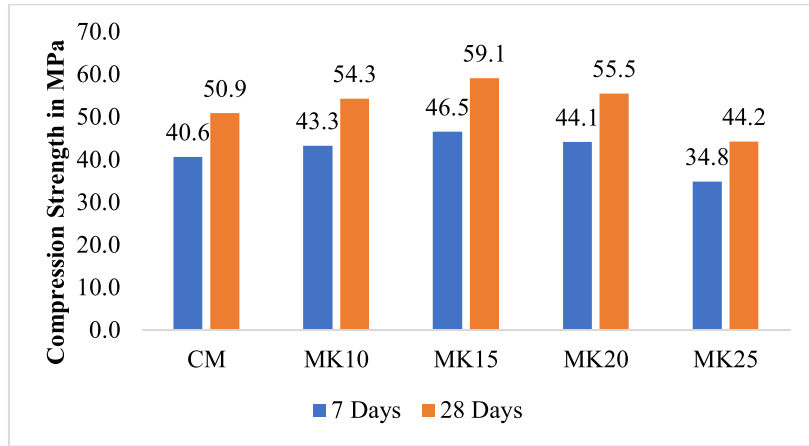


Fig. 11. Compressive strength of SCC made with MK (MPa)

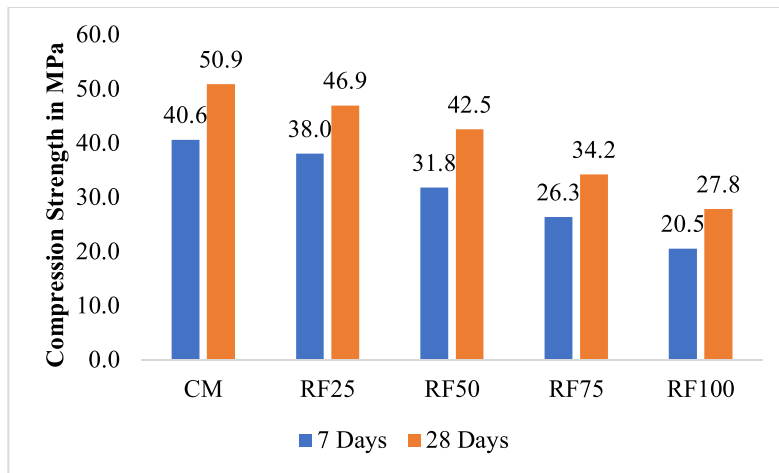


Fig. 12. Compressive strength of SCC made with RFA (MPa).

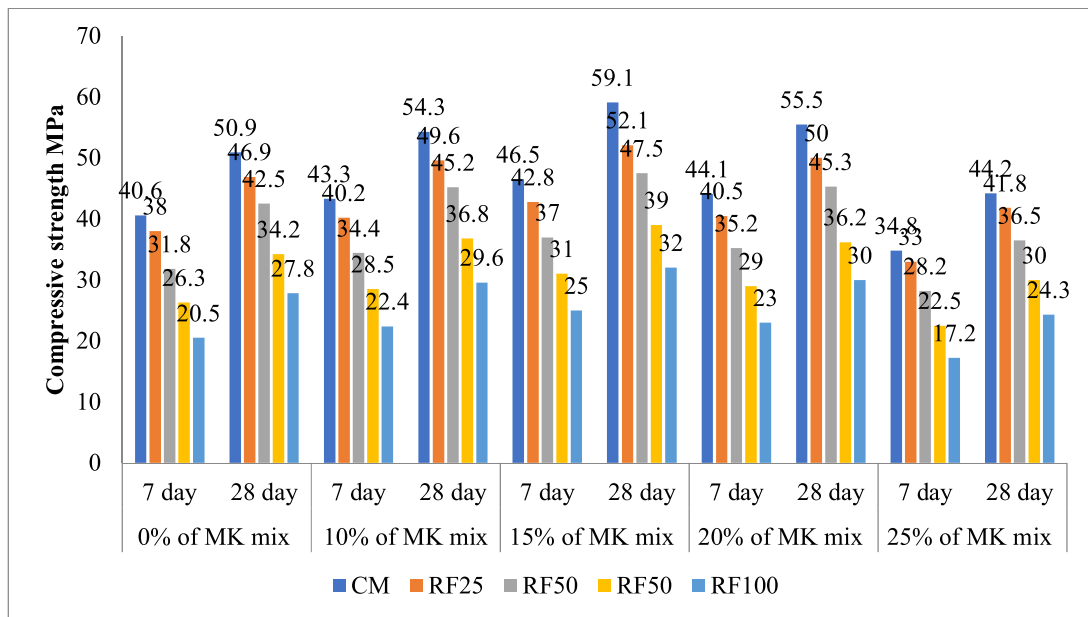


Fig. 13. Compressive strength of RF-SCC made with metakaolin (MPa).

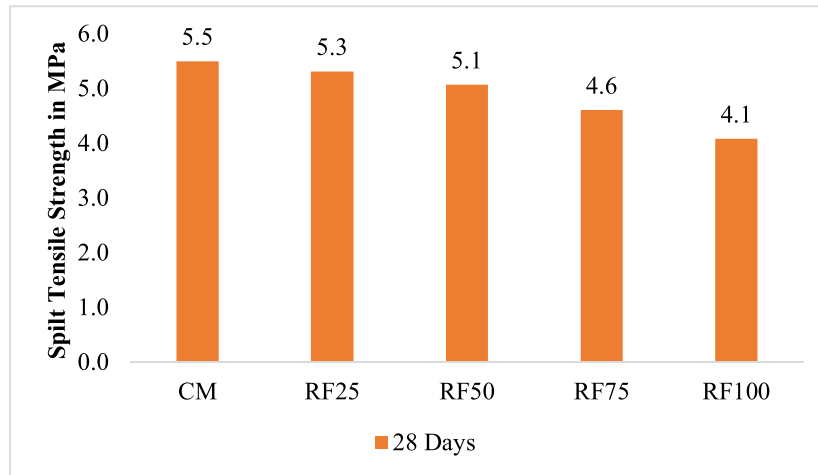


Fig. 14. Split tensile strength of SCC made with MK (MPa).

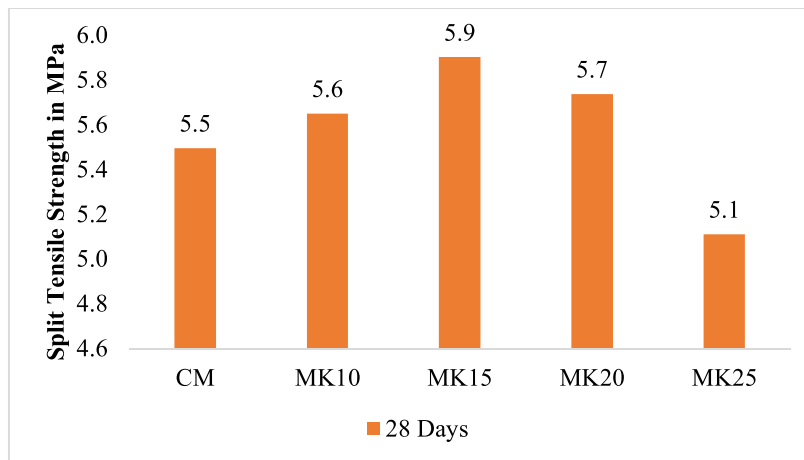


Fig. 15. Split tensile strength of SCC made with RFA (MPa).

MK can somewhat offset the strength loss brought on by RFA, according to the combined effect of RFA and MK. For example, the RF25 mix with 15% MK exhibits a decline of just 8.5% in comparison to the control, while the drop without MK is 22.3%. The RF50 decreases by 16.8% at 15% MK, which is less drastic than the 21.7% decline at 0% MK. These results suggest that up to 15% MK can enhance matrix integrity and binding qualities, lessening the adverse impacts of recycled aggregate and producing a mix design that is sustainable and structurally sound [39].

cating increases of around 1.8%, 7.3%, and 3.6%, respectively. As reported by Muduli and Mukharjee (2020) [41], this improvement is ascribed to MK's pozzolanic reaction, which strengthens the link between the aggregates and cement matrix and refines the microstructure. The tensile strength decreased to 5.1 MPa at 25% MK, a 7.3% decrease from the control mix. This decrease implies that too much MK content could dilute cementitious chemicals, emphasizing that the maximum performance advantage is provided by an ideal dosage of about 15%.

4.2.2. Split tensile strength

4.2.2.1. Impact of MK on the split tensile strength of RF-SCC. The 28-day split tensile strength of concrete mixtures with different proportions of metakaolin (MK) is shown in the Fig. 14. A tensile strength of 5.5 MPa was attained by the control mix (CM). The strength rose to 5.6 MPa, 5.9 MPa, and 5.7 MPa with 10%, 15%, and 20% MK replacement, indi-

4.2.2.2. Impact of RFA on the split tensile strength of RASCC. The 28-day split tensile strength of concrete with different percentages of recycled fine aggregate (RFA) substitution is displayed in the Fig. 15. The tensile strength of the control mix (CM) was 5.5 MPa. The strengths were 5.3 MPa, 5.1 MPa, 4.6 MPa, and 4.1 MPa, respectively, when 25%, 50%, 75%, and 100% RFA were used in place of natural fine

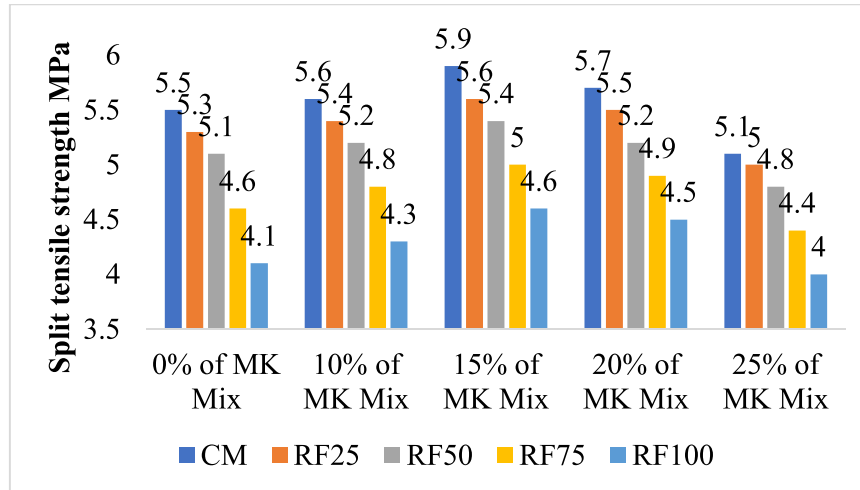


Fig. 16. Split tensile strength of RF-SCC made with metakaolin (MPa).

aggregate. In comparison to the control, these indicate strength decreases of roughly 3.6%, 7.3%, 16.4%, and 25.5%. The primary cause of the decline in tensile strength is the recycled aggregates' poorer physical characteristics, which include increased porosity and decreased bonding capacity. Higher RFA replacement levels have a negative impact on the tensile performance of concrete because they weaken the matrix's overall cohesiveness and integrity as the RFA concentration rises.

4.2.2.3. Combined effect of RFA and MK on split tensile strength. The 28-day split tensile strength of SCC mixes with different proportions of RFA and MK is shown in the Fig. 16. Mixtures with RFA replacement exhibit a declining trend when compared to the control mix with 0% MK and 5.5 MPa strength. RF25, RF50, RF75, and RF100 all cause reductions of 3.6%, 7.3%, 16.4%, and 25.5% at 0% MK, respectively. This suggests that tensile strength is negatively impacted by increased RFA content because of its porous nature and lower interfacial bonding as stated by Bayraktar et al. (2022) [40]. MK, on the other hand, increases strength. The control mix exhibits a 7.3% increase over the initial CM at 15% MK. MK has a beneficial effect even in RFA mixes; for example, RF25 with 15% MK increases strength to 5.6 MPa, which is very similar to CM. Therefore, MK successfully counteracts the detrimental effects of RFA, particularly at 10–15% levels.

4.2.3. Flexural strength

4.2.3.1. Impact of MK on flexural strength. The 28-day flexural strength of concrete with different metakaolin (MK) contents is represented in the Fig. 17. The flexural strength of the control mix (CM)

is 6.2 MPa. The strength improves to 6.3 MPa, 6.6 MPa, and 6.4 MPa with the addition of 10%, 15%, and 20% MK, suggesting increases of around 1.6%, 6.5%, and 3.2% above the control. These benefits are ascribed to MK's pozzolanic effect, which strengthens the interfacial connection, densifies the matrix, and improves the microstructure. However, the flexural strength decreases to 5.7 MPa (an 8.1% decrease) at 25% MK, most likely as a result of the dilution effect and lower cementitious content. All things considered, MK enhances flexural function up to an ideal dosage of 15%, after which strength starts to decrease.

4.2.3.2. Impact of RFA on flexural strength. The 28-day flexural strength of concrete with varying amounts of recycled fine aggregate (RFA) replacement is shown in the Fig. 18. A flexural strength of 5.5 MPa is recorded for the control mix (CM). A discernible decrease in strength occurs as the RFA content rises: the strengths of RF25, RF50, RF75, and RF100 are 5.3 MPa, 5.1 MPa, 4.6 MPa, and 4.1 MPa, respectively. Comparing them to the control mix, they represent decreases of roughly 3.6%, 7.3%, 16.4%, and 25.5%. The primary cause of the decrease is the decreased quality of recycled aggregates, which often have weak bonding properties, lower strength, and more water absorption. The internal structure of the concrete deteriorates with increasing RFA content, resulting in decreased flexural performance and highlighting the necessity of performance-enhancing additives.

4.2.3.3. Combined effect of RFA and MK on flexural strength. The 28-day flexural strength of concrete mixes with different amounts of RFA and MK is

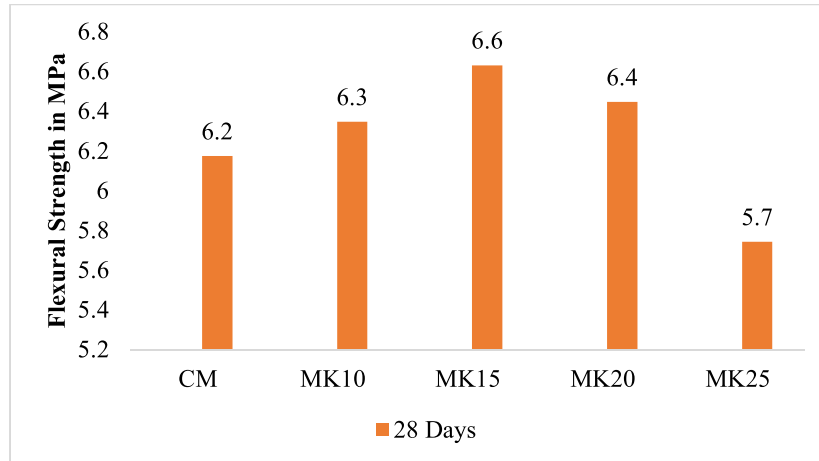


Fig. 17. Flexural strength of SCC made with MK (MPa).

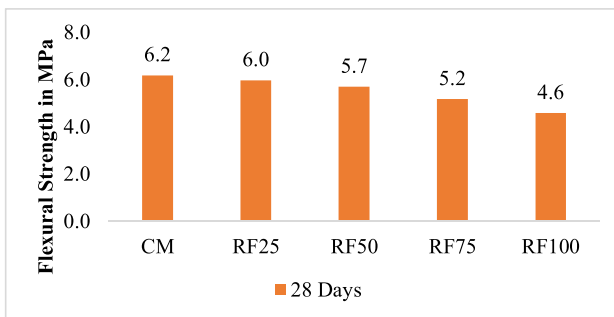


Fig. 18. Flexural strength of SCC made with RFA (MPa).

displayed in the Fig. 19. The flexural strength of the control mix at 0% MK is 6.2 MPa. The strength reduces as the RFA concentration rises; in comparison to the control mix, RF25, RF50, RF75, and RF100 exhibit reductions of roughly 3.2%, 8.1%, 16.1%, and 25.8%, respectively. The lower quality and weaker bonding properties of recycled aggregates are to blame for this reduction. MK enhances flexural performance, nevertheless. CM strength rises by 6.5% at 15% MK, while RFA mixes exhibit comparable patterns. For example, the RF50 at 15% MK is 6.0 MPa, which is 5.3% higher than its corresponding value at 0% MK. Therefore, when utilized to its full potential, MK improves flexural strength, thereby offsetting the disadvantages of RFA.

5. Microstructure of recycled fine aggregate (RFA) in SCC

The basic components of concrete are a cementitious matrix, fine (sand) and coarse aggregates, as well as an essential area between the cement paste and coarse aggregates called the interfacial transition

zone (ITZ) [33, 69, 70]. Concrete has a complicated, three-phase structure as a result. The durability and mechanical behavior of concrete are significantly influenced by the ITZ. It makes up a substantial amount of the cement paste volume, estimated at between 20 to 40% if we assume an average thickness of 40 μm , despite being a rather thin layer, usually ranging between 75 and 100 μm [71]. The ITZ is sometimes referred to as the “weak link” in the matrix and, despite its tiny physical size, is typically the weakest zone in the concrete microstructure [72–74].

Scanning electron microscopy (SEM) examinations at the microscopic level shed more light on this phenomenon. Fig. 20 presents the microstructural features of the SCC mixture incorporating 15% MK and 50% RFA. The interfacial transition zone (ITZ) around the recycled aggregate contains fine, needle-shaped ettringite crystals, typically ranging from 3 to 10 μm in length. A dense and tightly packed C–S–H gel with a characteristic foil-like texture is visible across the matrix. The ITZ thickness is measured to be around 15–25 μm , which is considerably lower compared to the control mix (30–45 μm). Pore cavities within this region are also smaller, approximately 21–54 μm , reflecting better particle packing and reduced voids as a result of the pozzolanic contribution of MK. Conversely, a comparatively more porous and heterogeneous interfacial region was observed in mixes containing 100% RFA. Scanning electron microscopy (SEM) pictures of the 15%MK + 50%RFA and 15%MK + 100%RFA combinations are displayed in Figs. 21 and 22.

In contrast to the 15% MK + 100% RFA mixture, which exhibits greater pore size variability and a less compact paste–aggregate interface, the 15% MK + 50% RFA mixture shows a more homogeneous and denser paste–aggregate interface with noticeably

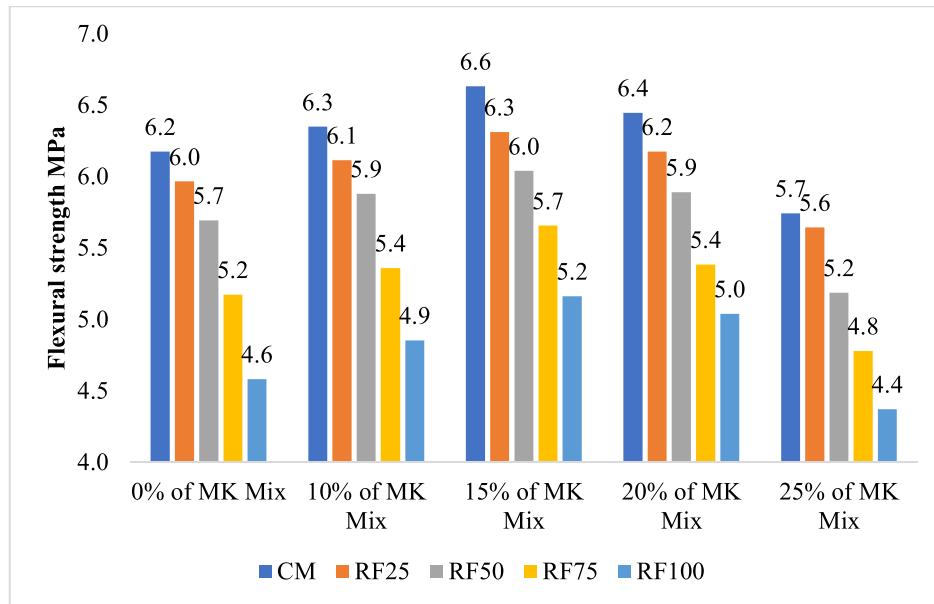


Fig. 19. Flexural strength of RF-SCC made with metakaolin (MPa).

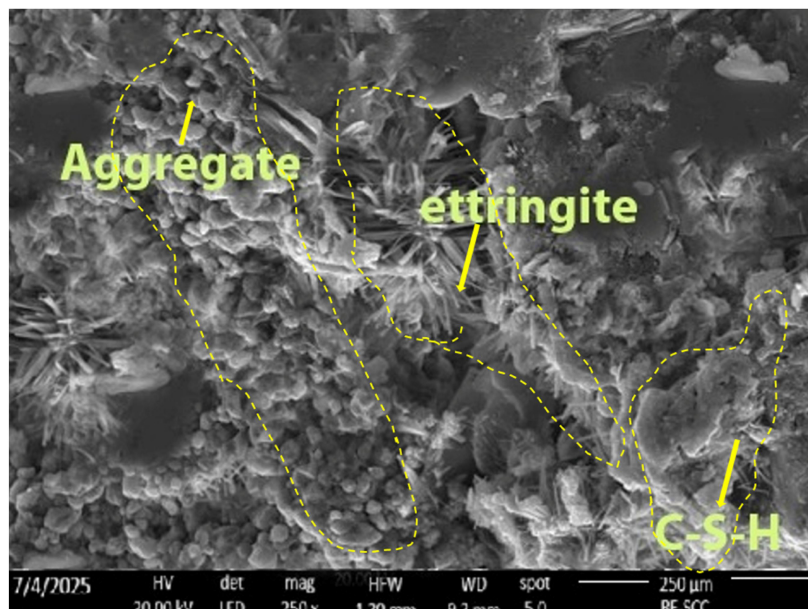


Fig. 20. Completely filled mixtures contain 15%MK+50%RFA.

smaller pore sizes (Figs. 21 and 22). A comparatively less compact interfacial transition zone (ITZ) was observed in SCC containing 100% recycled fine aggregate. This was ascribed to inadequate bonding between the RFA and the cement paste. The overall strength and durability of the matrix may have been compromised by the porous microstructure created by the presence of adhering old mortar, increased porosity, and fine impurities. These structural flaws may have a detrimental effect on the cohesiveness of

the matrix and aggregates, which could account for the observed decrease in microhardness and compressive strength.

Furthermore, compared to the other mixes, the 15% MK + 50% RFA mixture exhibits smaller micropores. The extremely effective pozzolanic reactions linked to the 5% and 10% MK concentrations could be the cause of this. With less calcium hydroxide (CH) left over, a more compact network of hydration products is created. This implies that metakaolin (MK) and CH

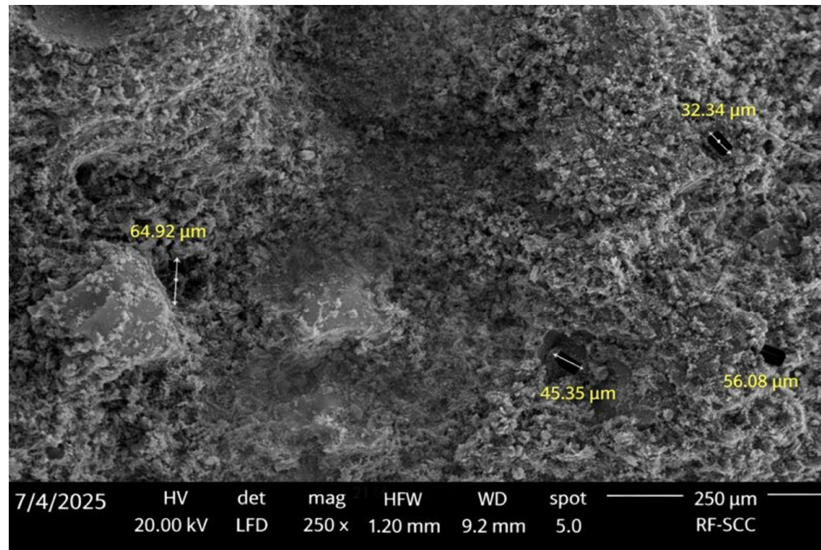


Fig. 21. SEM image of 15% MK + 50% RF-SCC showing a relatively denser matrix with fewer and more uniformly distributed pores.

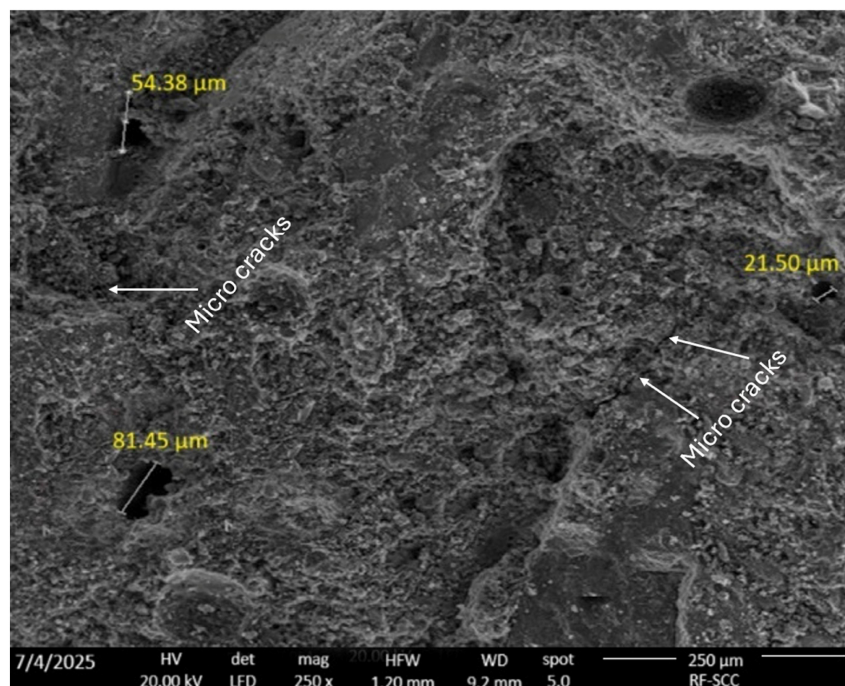


Fig. 22. SEM image of 15% MK + 100% RF-SCC showing increased pore size variability with the presence of both small and comparatively larger pores.

have an efficient pozzolanic reaction, which refines the capillary porosity of the binder. These results are in line with the porosity analysis's findings.

Nevertheless, SEM analysis also showed that the interface between the new cement paste and the old adhering mortar had more microcracks and voids in mixes that used recycled fine aggregates (Fig. 22). Limited water availability in the interfacial zone and inadequate hydration may be the cause of this. Ad-

ditionally, the density of the cement paste matrix varied between conventional and RF-based concrete, as shown in SEM images (Fig. 22). Compared to normal mixes, which demonstrated a denser and more compact bonding structure, the microstructure of recycled concrete indicated a comparatively less dense matrix [37, 38]. In the end, our findings confirm the widely held belief that the total strength of the concrete increases with the strength of the link between

Table 7. Cradle-to-gate CO₂ emissions for selected SCC mixes.

Mix Type	Cement (kg/m ³)	MK (kg/m ³)	NF (kg/m ³)	RFA (kg/m ³)	CO ₂ _cement (kgCO ₂ /m ³)	CO ₂ _MK	CO ₂ _NF	CO ₂ _RFA	Total CO ₂ (kgCO ₂ /m ³)
Normal SCC (CM)	436.0	0.0	919.0	0.0	375.0	0.0	7.03	0.00	382.0
15% MK + 50% RFA	370.6	65.4	459.5	459.5	318.7	11.8	3.52	0.92	334.9
15% MK + 100% RFA	370.6	65.4	0.0	919.0	318.7	11.8	0.00	1.84	332.3

the MK and cement paste [71, 75]. Therefore, optimizing the ITZ can be crucial to improving the performance of sustainable concrete, particularly in mixes based on MK.

6. Environmental impact and life-cycle cost assessment

6.1. Environmental impact assessment (LCA-based quantification)

A cradle-to-gate Life Cycle Assessment (LCA) was performed for three SCC mixes: conventional SCC, 15% MK + 50% RFA, and 15% MK + 100% RFA. The study followed ISO 14040/44 guidelines [58], evaluating CO₂ emissions from the production of cement, metakaolin (MK), natural fine aggregate (NF), recycled fine aggregate (RFA), and admixtures. Emission factors were taken from published concrete sustainability data [59–65].

Emission Factors Used:

- Cement: 0.86 kg CO₂/kg
- Metakaolin: 0.18 kg CO₂/kg
- Natural sand (NF): 0.00765 kg CO₂/kg
- Recycled fine aggregate (RFA): 0.002 kg CO₂/kg

Table 7 presents the cradle-to-gate CO₂ emissions for the selected SCC mixes. The conventional SCC mix generates 382kg CO₂/m³. Replacing 15% of cement with MK and partially substituting natural sand with RFA (50%) reduces CO₂ emissions by around 12.3%, mainly due to lower cement use and partial replacement of natural aggregates [62–64]. The 15% MK + 100% RFA mix achieves the highest reduction, approximately 13%, through full aggregate replacement and the lower embodied carbon of MK. These results show that MK–RFA combinations can considerably lower the carbon footprint of SCC [58–65].

6.2. Life cycle cost (LCC) analysis

A life-cycle cost assessment was carried out considering material, construction, and maintenance costs. Unit costs were obtained from Indian construction cost databases and literature [66]. To improve transparency and ensure reproducibility of the life-cycle

cost (LCC) assessment, the total material cost per cubic meter of SCC was decomposed into its principal constituents, namely cement, metakaolin (MK), natural fine aggregate (NF), recycled fine aggregate (RFA), and a combined category denoted as other materials. Unit prices were adopted from standard Indian construction cost datasets applicable to Madhya Pradesh [52]. The unit costs used were ₹8.0/kg for cement, ₹12.0/kg for MK, ₹0.80/kg for NF, and ₹0.30/kg for RFA.

The other materials component represents the collective cost of coarse aggregate, mixing water, minor admixtures, and handling and processing losses. These components were kept constant for all mixes, and therefore their cost contribution varies only marginally among mixtures. The resulting material cost bifurcation and total material cost for the selected SCC mixes are presented in Table 8.

The variation in superplasticizer costs among the selected mixes was negligible and therefore not considered in the LCC calculations. Table 9 summarizes the life-cycle costs of the selected SCC mixes. The 15% MK + 50% RFA mix lowers total life-cycle cost by about 5.7% compared to conventional SCC, primarily because of reduced material costs and lower maintenance [62, 67]. The 15% MK + 100% RFA mix offers the highest reduction, around 9.4%, indicating the most cost-effective option among the studied mixes [67].

Integrating LCA and LCC results shows that SCC mixes with MK and RFA improve both environmental performance and cost efficiency. Cement reduction and substitution of natural sand with recycled aggregates reduce CO₂ emissions by 12–13%, while material savings and improved durability contribute to 6–10% cost reduction. Overall, the 15% MK + 50% RFA and 15% MK + 100% RFA mixes are technically practical, environmentally sustainable, and economically advantageous [58–68].

Fig. 23 illustrates the total life-cycle cost and cradle-to-gate CO₂ emissions for the studied SCC mixes. Both the 15% MK + 50% RFA and 15% MK + 100% RFA mixes show reductions in LCC and CO₂ compared to conventional SCC, highlighting the environmental and economic benefits of partially replacing cement and natural sand with MK and RFA.

Table 8. Material cost bifurcation for selected SCC mixes (₹/m³).

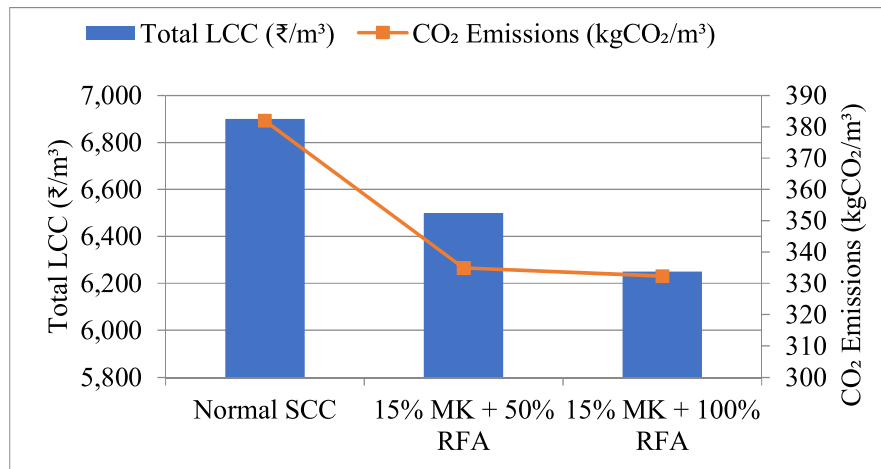
Mix Type	Cement	MK	NF	RFA	Other Materials*	Total Material Cost
Normal SCC	3,488.00	0.00	735.20	0.00	876.80	5,100
15% MK + 50% RFA	2,964.80	784.80	367.60	137.85	594.95	4,850
15% MK + 100% RFA	2,964.80	784.80	0.00	275.70	624.70	4,650

*Includes coarse aggregate, mixing water, minor admixtures, and handling and processing losses.

Table 9. Life-cycle cost summary for selected SCC mixes.

Mix Type	Material Cost (₹/m ³)	Construction Cost (₹/m ³)	Maintenance Cost (₹/m ³)*	Total LCC (₹/m ³)
Normal SCC	₹5,100	₹1,000	₹800	₹6,900
15% MK + 50% RFA	₹4,850	₹1,000	₹650	₹6,500
15% MK + 100% RFA	₹4,650	₹1,000	₹600	₹6,250

*Maintenance cost decreases with MK due to improved performance.

**Fig. 23.** Total life-cycle cost and cradle-to-gate CO₂ emissions for the studied SCC mixes.

7. Conclusions

Based on the experimental investigation, the following key conclusions and scientific contributions are presented:

- The experimental programme enabled a clear understanding of how recycled fine aggregates (RFA) and metakaolin (MK) jointly influence the behaviour of self-compacting concrete (SCC). All mixes satisfied EFNARC criteria for filling and passing ability, demonstrating that workable SCC can still be produced even at high RFA levels when an appropriate binder modification is used.
- Metakaolin improved the workability of SCC up to an optimum replacement level of 15% due to its filler effect and enhanced particle packing, whereas higher dosages increased paste viscosity and reduced flow.
- A consistent decline in compressive strength was observed with increasing RFA content, with the maximum reduction approaching 45% at full replacement.
- This study quantifies the extent of strength loss more precisely than many earlier works, helping resolve inconsistencies in the reported influence of RFA on SCC. In contrast, the inclusion of MK enhanced strength up to an optimum of 15%, after which excessive fineness and reduced particle packing resulted in strength reduction.
- Tensile and flexural strengths reflected the same behaviour, confirming that moderate MK incorporation can counteract the drawbacks of RFA. A major contribution of this study is the identification of a performance-balanced mix: SCC containing 15% MK combined with 50–100% RFA achieved strengths comparable to natural aggregate SCC, demonstrating a previously under-explored synergy between the two materials.
- Microstructural observations further verified this interaction. Mixes containing up to 15% MK exhibited a denser interfacial transition zone and fewer microcracks, explaining the improvements in strength and durability. This microstructural evidence fills a notable gap in literature that

has not clearly connected MK's refinement effects with the adhered mortar characteristics of RFA.

- Overall, the study establishes a scientifically supported pathway for producing sustainable SCC using high proportions of RFA without compromising essential engineering performance. The findings offer practical mix-design guidance and contribute new experimental and microstructural insights that address long-standing gaps and contradictions in earlier research.
- Life cycle assessment results confirm that 15% MK with 50–100% RFA achieves 12–13% reduction in cradle-to-gate CO₂ emissions compared to conventional SCC. Life-cycle cost analysis shows a 6–10% reduction in total life-cycle cost for MK–RFA-based SCC, demonstrating its economic feasibility along with sustainability benefits.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution

Mahakavi P: Supervision, Correction.

Sachin Tiwari: Investigation, Analysis, Write up.

Data availability

No Data Availability.

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