



Waste Foundry Sand and Silica Fume in Sustainable Concrete: Mechanical Performance, Microstructural Characteristics, and Life Cycle Assessment

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ABSTRACT

Using industrial by-products in concrete is an effective strategy for reducing environmental impacts while enhancing material sustainability. This study investigates the incorporation of waste foundry sand (WFS) and silica fume (SF) into M40 concrete within an integrated experimental–environmental framework, linking mechanical, microstructural, durability, and life cycle assessments. Concrete mixtures with 0–30% WFS as a fine aggregate replacement and a constant 7% SF as a cement replacement were evaluated for workability, strength characteristics, carbonation resistance, microstructural characteristics using SEM–EDS analysis, and cradle-to-gate environmental impacts. Among the mixtures tested, the 10% WFS–7% SF combination delivered the best overall performance, achieving a 37.2% increase in 28-day compressive strength relative to the control mix, along with corresponding improvements in split tensile and flexural strengths. Microstructural analysis indicated improved matrix densification and a refined interfacial transition zone in the optimized mixture. Life cycle assessment using Mobius Ecochain, Ecoinvent v3.9.1, and the ReCiPe midpoint method showed reductions in climate change potential, fossil resource use, and land occupation for all WFS–SF mixtures relative to conventional concrete. The results confirm that the controlled use of WFS and silica fume can improve structural performance while reducing environmental impacts, supporting the sustainable valorization of foundry waste in concrete production.

Keywords: Waste foundry sand; Silica fume; Sustainable concrete; Microstructural analysis; Life cycle assessment.

1. INTRODUCTION

Concrete remains the most widely used construction material after water due to its versatility, durability, and the availability of its constituent materials (Ahmad *et al.* 2022; Kumar *et al.* 2023). Global production has exceeded 4.5 billion tons annually, reflecting significant demand driven by infrastructure expansion and urban development. However, conventional concrete production carries considerable environmental impacts (Mack-Vergara, 2024). Cement manufacturing alone accounts for nearly 7–8% of global carbon dioxide emissions, primarily from the calcination of limestone and the high energy requirements of clinker production (Moolchandani, 2025; Chen *et al.* 2025).

In addition to emissions from cement production, the unregulated extraction of natural aggregates further intensifies the environmental burden associated with concrete production. Excessive sand mining has been linked to riverbed erosion, disruption of aquatic ecosystems, and depletion of natural resources. These concerns have prompted the construction industry to explore alternative materials capable of reducing dependence on conventional aggregates and cement without compromising performance (Norbidin, 2024).

Among available alternatives, industrial by-products have attracted growing attention as substitutes for conventional construction materials (Moolchandani, 2025). Reusing these materials conserves natural resources and helps address the growing challenge of industrial waste disposal. One such material is waste foundry sand (WFS), a by-product of metal casting processes (García *et al.* 2024; Siddique *et al.* 2009; Siddique and Singh, 2011; Tavakoli *et al.* 2018). High-quality silica sand is repeatedly used to produce molds and cores in foundry operations. After several cycles, the sand loses its required properties and is discarded. Large quantities of WFS are generated each year, and most are disposed of in landfills, raising environmental and economic concerns (Pugh *et al.* 2026). Owing to its fine particle size and silica-rich composition, WFS has shown promising potential as a partial replacement for natural fine aggregate in concrete.

Complementing WFS, silica fume (SF) is widely recognized as an effective supplementary cementitious material in high-performance concrete. Produced as an ultrafine by-product during the manufacture of silicon and ferrosilicon alloys, SF contains a high proportion of amorphous silica and exhibits strong pozzolanic reactivity (Moolchandani, 2025; Mehta and Ashish, 2020). When incorporated into

cementitious systems, SF reacts with calcium hydroxide generated during cement hydration to form additional calcium silicate hydrate (C–S–H), thereby refining the pore structure and enhancing strength and durability (Sharma, 2022).

Table 1. Comparison of previous studies and identified research gaps in WFS-based concrete

Author(s)	Methodology	Key Findings	Research Gap
Siddique <i>et al.</i> 2009	Experimental study with 10–30% replacement of fine aggregate	Marginal increase in compressive, tensile, and flexural strength	Limited long-term durability and environmental impact studies
Sharma, 2020	Experimental analysis using WFS, silica fume, fibers, and C&D waste	Compressive strength improved with the combined use of WFS and admixtures	Lack of optimization models for mix design
Pugh <i>et al.</i> 2026	Review and synthesis of published studies	WFS can partially replace natural sand effectively; it highlights variability in performance	Lack of comprehensive life cycle and durability studies
Niyonyungu <i>et al.</i> 2025	Meta-analysis and decision framework development	Provides a structured evaluation of WFS reuse, considering leachate safety and performance	Regulatory pathways and large-scale implementation remain unclear
Tangadagi and Ravichandran, 2024	Experimental evaluation and life cycle assessment	WFS improves the engineering properties and sustainability of SCC	Need for large-scale field validation
Mack-Vergara, 2024	Life cycle assessment using OpenLCA	High-performance concrete showed better environmental performance	Requires primary data and regional analysis
Barbhuiya and Das, 2023	Review of LCA methodologies and applications	LCA is essential for evaluating the sustainability of building materials	Need for standardized datasets and integration with the circular economy
Ghayouri <i>et al.</i> 2025	Performance evaluation of high-strength concrete with silica fume and metakaolin	Optimal compressive strength was achieved at 7% silica fume	Need for integrated evaluation frameworks
Moolchandani, 2025	State-of-the-art review	FA, SF, and MSP improve mechanical and environmental performance	Need for integrated sustainability evaluation frameworks
Choi <i>et al.</i> 2025	Development of the sustainability index (SCI) integrating environmental, economic, and social impacts.	Enables quantitative sustainability evaluation of concrete	Application to different regions and materials required

Although the individual effects of WFS and SF in concrete have been widely reported, studies investigating their combined use remain relatively limited. The simultaneous use of WFS and SF may provide complementary benefits, with WFS improving particle packing through filler action and SF enhancing matrix densification through pozzolanic reaction. However, the extent to which these mechanisms interact to influence mechanical performance and durability remains insufficiently established.

Moreover, existing studies have predominantly focused on isolated aspects of performance, such as strength or durability, with limited research integrating mechanical behavior, microstructural characterization, and environmental impact assessment within a unified framework. In particular, comprehensive investigations that couple SEM–EDS microstructural analysis with Life Cycle Assessment (LCA) to evaluate the structural and environmental implications of combined WFS–SF concrete remain scarce.

To address these gaps, the present study investigates the synergistic use of WFS and SF in M40 concrete using an integrated experimental and environmental assessment framework. The study evaluates fresh and hardened mechanical properties, carbonation resistance, and microstructural development using SEM–EDS, and assesses cradle-to-gate environmental impacts through LCA to identify an optimized, sustainable concrete mixture that balances structural performance with environmental efficiency.

1.1 Research Objectives

The objectives of the present investigation are:

- To evaluate the feasibility of using waste foundry sand as a partial replacement for natural fine aggregate in concrete mixtures.
- To examine the influence of silica fume as a partial cement replacement on the performance of WFS-based concrete.
- To investigate the mechanical properties of the developed mixtures, including compressive, split tensile, and flexural strengths.
- To assess durability performance through carbonation resistance testing.
- To analyze the microstructure of the modified concrete matrix using SEM–EDS.
- To quantify the environmental impacts of the developed mixtures using LCA.

2. EXPERIMENTAL WORK

2.1 Materials and Characterization

2.1.1 Cement

Ordinary Portland Cement (OPC) conforming to IS 269:2015 served as the primary binder. The cement's physical properties were determined through standard laboratory tests. Fineness was 3.2% retained on a 90 μm sieve. The initial and final setting times were 35 min and 600 min, respectively. Although the final setting time was relatively high, it remained within the permissible limit specified by IS 269. This delayed setting behavior may be attributed to the fineness, gypsum content, and clinker composition of the specific cement batch used. Soundness, measured using the Le Chatelier apparatus, was 2.5 mm, indicating satisfactory volumetric stability.

2.1.2 Waste Foundry Sand (WFS)

WFS was purchased from local metal casting industries in and around Chennai, Tamil Nadu, India. The material exhibited a specific gravity of 2.65 and a fineness modulus of 1.2, indicating significantly finer particles than conventional river sand. Approximately 90% of the material passed the 75 μm sieve. Water absorption was measured at 1.8%, and the apparent density was 1.65 g/cm³. Fig. 1 shows the collected WFS sample.



Fig. 1: Waste foundry sand collected from local metal casting industries

SEM analysis (Fig. 2) revealed angular to sub-angular particle morphology with a rough surface texture, which may enhance mechanical interlocking within the cement matrix. EDS analysis (Fig. 3) confirmed that WFS is predominantly siliceous, with high oxygen and silicon contents and notable amounts of iron and aluminum. Minor quantities of calcium, magnesium,

sodium, titanium, bismuth, and trace elements were also observed (Table 2). The presence of these minor metallic contaminants in the WFS reflects the material's industrial origin and residual deposition from repeated foundry operations.

The silica-rich composition enhances particle-packing efficiency, while the irregular morphology improves internal bonding. However, iron-rich phases may affect workability at higher replacement levels.

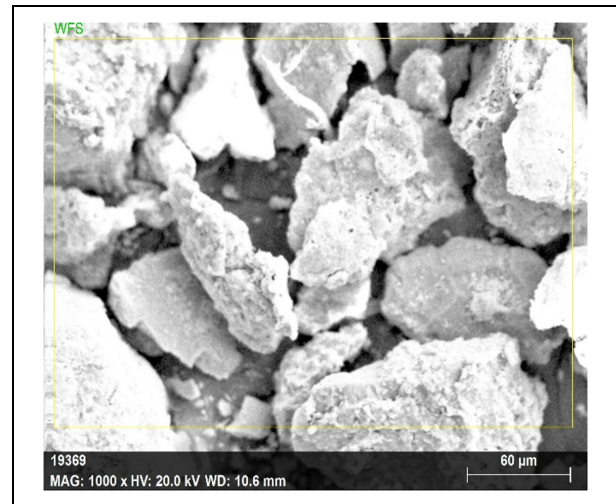


Fig. 2: SEM micrograph of WFS showing angular to sub-angular particle morphology with rough surface texture

Table 2. Elemental composition of WFS obtained from EDS analysis

Element	Weight (%)	Atomic (%)
O	35.43	55.55
Si	26.29	23.48
Fe	22.15	9.95
Al	7.31	6.80
Bi	4.50	0.54
Na	1.32	1.45
Mg	0.94	0.97
Ca	1.92	1.20
Ti	0.15	0.08

2.1.3 Silica Fume

Industrial-grade silica fume was used as a supplementary cementitious material. The material exhibited a bulk density of 200–300 kg/m³ and a specific gravity of 2.2. Particle size ranged from 0.1–0.5 μm , with an average diameter less than 1 μm , and a specific surface area of 18,000–20,000 m²/kg. The silica fume contains more than 90% silicon dioxide (SiO₂) and has a loss on ignition below 2%. The high amorphous silica content contributes to strong pozzolanic reactivity. Fig. 4 depicts the silica fume used in the study.

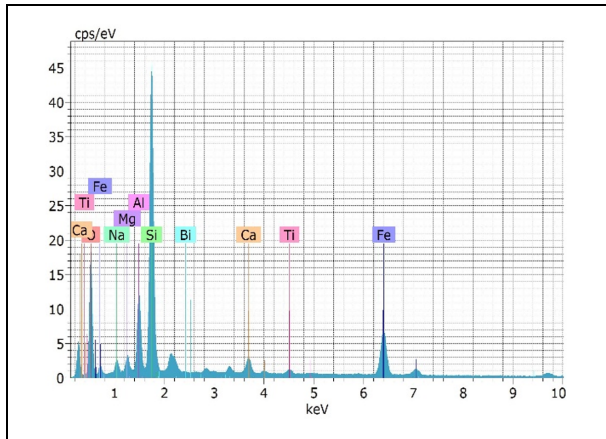


Fig. 3: EDS spectrum of WFS showing a predominantly siliceous composition with minor and trace elemental constituents



Fig. 4: Silica fume used as supplementary cementitious material

2.1.4 Aggregates

Fine aggregates consisted of clean, well-graded manufactured sand conforming to the grading requirements of IS 383:2016, with a specific gravity of 2.65 and a fineness modulus of 2.8, corresponding to Zone I grading. Coarse aggregates consisted of crushed stone with a nominal maximum size of 20 mm, specific gravity of 2.74, and water absorption of 0.5%, conforming to the grading and physical requirements specified in IS 383:2016.

2.2 Mix Design and Proportions

Concrete mix proportions were determined in accordance with IS 10262:2019 for the design of M40 grade concrete. The mix was designed to achieve a target slump of 75–100 mm with a water–cement ratio of 0.36. To maintain the required workability and counteract the reduction in flowability caused by the incorporation of mineral admixtures, a polycarboxylate ether–based superplasticizer was incorporated at 0.5% of the cement

weight in all trial mixtures. The detailed proportions of the mixtures adopted in this investigation are presented in Table 3. The reference mix was prepared with a cement: fine aggregate (FA): coarse aggregate (CA) ratio of 1:1.72:3, maintaining the water–cement ratio at 0.36.

For the experimental investigation, four concrete mixtures were produced. WFS was used as a partial replacement for natural fine aggregate at 0%, 10%, 20%, and 30% by weight (Ahmad *et al.* 2022). In addition, the silica fume replacement level was maintained at 7% by weight of cement in all modified mixtures, based on findings from previous studies that have consistently reported that silica fume contents in the range of 5–10% provide optimal improvements in strength and durability while minimizing adverse effects on workability and material cost (Ghayouri *et al.* 2025; Farahani *et al.* 2023; Gražulytė *et al.* 2020). A constant replacement level was adopted in the present study to isolate the influence of varying WFS content and to evaluate the synergistic interaction between WFS and silica fume under a fixed pozzolanic dosage.

Table 3. Mix proportions of control and WFS–SF-modified concrete mixtures

Mix	Cement (kg/m ³)	SF (kg/m ³)	FA (kg/m ³)	WFS (kg/m ³)	CA (kg/m ³)
Conventional	420	0	722.4	0	1260
Trial Mix 1	390.6	29.4	650.2	72.2	1260
Trial Mix 2	390.6	29.4	577.9	144.5	1260
Trial Mix 3	390.6	29.4	505.7	216.7	1260

2.3 Specimen Preparation and Curing

Concrete specimens were prepared and tested in accordance with IS 516:2021 and IS 5816:2021. Three specimen types were cast to evaluate the mechanical performance of the developed concrete mixtures. Cube specimens measuring 150 × 150 × 150 mm were used to determine compressive strength, while cylindrical specimens with a diameter of 150 mm and a height of 300 mm were prepared for split tensile strength testing. Prismatic specimens measuring 100 × 100 × 500 mm were cast to assess flexural strength.

After casting, the specimens were left undisturbed for 24 h before being removed from the molds. They were then placed in a water-curing tank and maintained under standard curing conditions until the specified testing age. Mechanical tests were conducted after 7 and 28 days of curing to evaluate the strength development of the concrete mixtures. The prepared specimens used for testing are shown in Fig. 5.



Fig. 5: Concrete specimens (cubes, cylinders, and prisms) for mechanical strength testing

2.4 Testing Procedures

2.4.1 Workability

The workability of the fresh concrete mixtures was determined using the slump test in accordance with IS 1199:2018 for each trial mix. The freshly mixed concrete was placed into the standard slump cone in three equal layers, and each layer was compacted with 25 strokes of a tamping rod to ensure proper consolidation. After filling and leveling the top surface, the cone was carefully lifted vertically without disturbing the concrete, allowing the concrete to subside under its own weight. The slump value was measured immediately to indicate the mixture's consistency and workability (Fig. 6).



Fig. 6: Slump test setup for workability evaluation of fresh concrete

2.4.2 Compressive Strength

Compressive strength testing was performed on 150 mm cubes using a calibrated Compression Testing Machine (CTM) until failure, as shown in Fig. 7. A minimum of three specimens per mix and age were tested. Compressive strength (f_c) was calculated using:

$$f_c = \frac{P_{failure}}{A_{cs}} \quad \dots (1)$$

where $P_{failure}$ is the failure load (N) and A_{cs} is the loaded cross-sectional area (mm²).



Fig. 7: Compressive strength test on a 150 mm concrete cube using a CTM

2.4.3 Split Tensile Strength

Cylindrical specimens (150 mm × 300 mm) were tested by applying compressive load along the diameter using a compression testing machine until failure. Split tensile strength (f_t) was calculated using:

$$f_t = \frac{2P}{\pi DL} \quad \dots (2)$$

where P is the load at failure (N), D is the cylinder diameter (mm), and L is the cylinder length (mm).



Fig. 8: Split tensile strength test setup for a 150 mm × 300 mm concrete cylinder

2.4.4 Flexural Strength

Beam specimens (100 mm × 100 mm × 500 mm) were subjected to a two-point loading system with a 400 mm span. Flexural strength was calculated (f_f) using:

$$f_f = \frac{PL}{bd^2} \quad \dots (3)$$

where P = load at failure (N), L = span (mm), b = width (mm), and d = depth (mm).



Fig. 9: Flexural strength test setup for 100 mm × 100 mm × 500 mm concrete prism

2.4.5 Carbonation Assessment

Carbonation depth was evaluated at 28 days and 450 days of exposure using a 1% phenolphthalein indicator solution. At each testing interval, concrete specimens were fractured to expose fresh internal surfaces, which were immediately sprayed with the indicator.

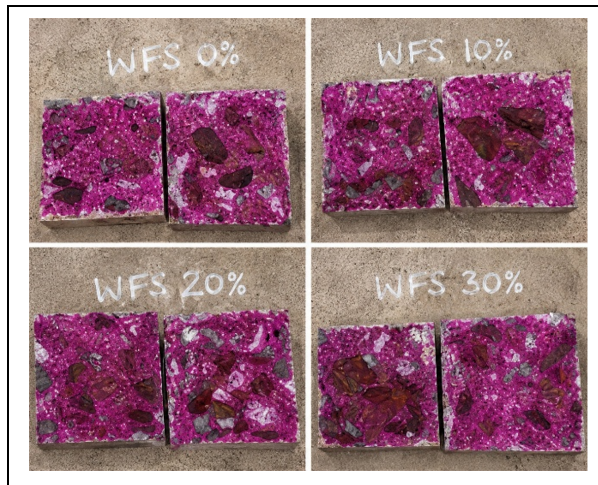


Fig. 10(a): Carbonation test results of concrete specimens at 28 days using 1% phenolphthalein indicator

The carbonation depth was measured as the distance from the exposed surface to the color-change boundary between the pink alkaline region and the colorless carbonated zone using a vernier caliper. Multiple measurements were recorded along the exposed face and averaged to obtain the representative carbonation depth for each specimen. The 28-day assessment provided an indication of early-age carbonation behavior, while the 450-day measurements

enabled the evaluation of long-term carbonation resistance under natural exposure conditions.

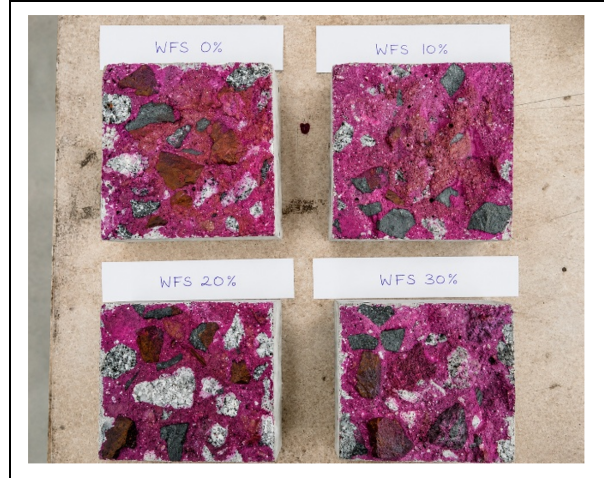


Fig. 10(b): Carbonation test results of concrete specimens at 450 days using 1% phenolphthalein indicator

2.4.6 SEM-EDS Analysis

SEM-EDS analysis was conducted on fractured specimens extracted from the interior of both the control and optimized mixes. Samples were oven-dried, mounted, and sputter-coated prior to imaging. SEM was used to assess hydration products, pore structure, and interfacial transition zones, while EDS provided semi-quantitative elemental composition to support the interpretation.

2.5 Life Cycle Assessment

LCA was conducted to evaluate the environmental impacts of the proposed concrete mixtures. The assessment followed the framework outlined in the ISO 14040:2006 and ISO 14044:2006 standards. Environmental impact modelling was performed using the Mobius Ecochain online platform, with background inventory data from the Ecoinvent v3.9.1 database. The ReCiPe midpoint impact assessment method was adopted to quantify the environmental burdens associated with the material system (Huijbregts *et al.* 2017). Mobius Ecochain was selected due to its compatibility with internationally recognized LCA databases, integration of the ReCiPe midpoint methodology, and suitability for cradle-to-gate environmental assessment of construction materials. Furthermore, the platform enables transparent and reproducible comparative evaluation of alternative concrete mixtures.

2.5.1 Functional Unit

The functional unit for the analysis was defined as 1 m³ of concrete, enabling direct comparison between the conventional mixture and the modified mixtures

containing waste foundry sand and silica fume. Environmental impacts, initially calculated for the laboratory batch volume of 0.0571 m³, were then normalized to the functional unit of 1 m³ of concrete using an appropriate scaling factor to ensure consistency and comparability in the life cycle assessment.

2.5.2 System Boundary

A cradle-to-gate system boundary was considered for the assessment. The system included the following life cycle stages:

- Extraction and processing of raw materials
- Production of cement and silica fume
- Processing and preparation of waste foundry sand
- Transportation of materials
- Concrete batching and casting processes

Processes including construction, maintenance, demolition, recycling, and end-of-life disposal were excluded from the present assessment, as the study focuses on comparative material-level environmental impacts during the production stage.

2.5.3 Impact Categories

Environmental impacts were evaluated using the following midpoint indicators:

- Climate change (kg CO₂-eq)
- Fossil resource depletion (MJ)
- Human toxicity – cancer effects (CTUh)
- Land use (pt)
- Water consumption (m³ world equivalent)

Inventory data for all materials and processes were obtained from standardized datasets available in the Ecoinvent database, ensuring methodological consistency and transparency in the environmental modelling process. If region-specific inventory datasets were available, they could be used. Comparative assessments were conducted under identical boundary conditions to maintain internal validity. In addition, sensitivity analysis was performed to assess the influence of variations in transportation distance and emission factors on the overall climate change impact results. The analysis indicated that such variations produced only minor changes in the comparative environmental rankings of the concrete mixtures, confirming the stability of the reported environmental trends.

The environmental benefit was calculated from the percentage reduction in each LCA impact category relative to the conventional concrete mix. The category-wise percentage reductions were averaged to obtain a composite environmental reduction score for each mixture, which was subsequently normalized with respect to the maximum observed composite reduction to derive a normalized environmental benefit score.

For each impact category, the percentage reduction was calculated as,

$$\text{Percentage reduction} = \frac{(I_c - I_t) \times 100}{I_c} \quad \dots (4)$$

where I_c is the impact of conventional concrete, and I_t is the impact of the trial mix. The final environmental benefit was obtained by averaging the reductions across all categories.

3. RESULTS AND DISCUSSION

3.1 Workability of Fresh Concrete

Slump test results presented in Table 4 demonstrated a progressive reduction in workability with increasing WFS content:

Table 4. Slump values of control and WFS–SF concrete mixes

Mix Type	WFS (%)	SF (%)	Slump (mm)
Conventional	0	0	110
Trial Mix 1	10	7	100
Trial Mix 2	20	7	95
Trial Mix 3	30	7	85

The 22.7% reduction in slump value (110 mm to 85 mm) at 30% WFS replacement is attributable to the fine particle size of WFS compared to conventional sand. Fine particles increase the specific surface area, requiring greater water film coverage. The addition of superplasticizer (0.5% by cement weight) effectively mitigated the reduction in workability, maintaining adequate slump values within acceptable limits specified in IS 456:2000 for a medium degree of workability.

The observed reduction in workability is consistent with previous studies reporting reduced slump in concrete containing WFS and SF due to increased fines content and surface area (Guney *et al.* 2010; Rao, 2003). However, chemical admixtures successfully restored workability to target ranges (Ghayouri *et al.* 2025), confirming the practical feasibility of higher WFS replacement levels with appropriate mix design optimization.

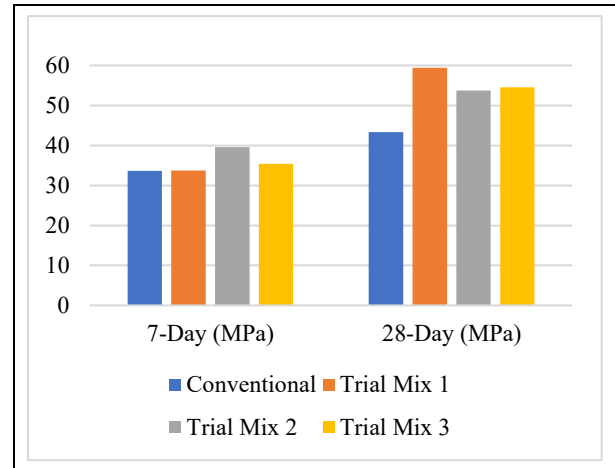
Table 5. Compressive strengths of control and WFS-SF concrete mixes

Mix Type	WFS (%)	SF (%)	7-day Compressive Strength (MPa)	28-day Compressive Strength (MPa)
Control	0	0	33.68	43.30
Trial Mix 1	10	7	33.73	59.44
Trial Mix 2	20	7	39.60	53.73
Trial Mix 3	30	7	35.37	54.50

3.2 Compressive Strength Development

The compressive strength results presented in Table 5 demonstrate that the incorporation of WFS and SF significantly influenced strength development, with the optimum replacement level varying between early-age and later-age performance. At 7 days, the mixture containing 20% WFS and 7% SF exhibited the highest compressive strength, indicating that moderate WFS incorporation may enhance early-age particle packing and matrix densification. However, at 28 days, the concrete containing 10% WFS and 7% SF achieved the maximum compressive strength of 59.44 MPa, representing a 37.2% improvement over the control mixture.

The enhanced long-term strength of the optimized mixture can be attributed to the synergistic action of WFS and SF; the fine WFS particles improve particle packing while SF contributes to secondary C-S-H formation through pozzolanic reaction, resulting in matrix densification and refinement of the interfacial transition zone. Although higher WFS replacement levels (20–30%) continued to exhibit strength values above that of the control mix, a reduction relative to the optimum mix was observed at 28 days. This behavior may be associated with excessive fines content at higher WFS dosages, which can increase water demand and reduce particle dispersion efficiency under constant water-to-binder ratio conditions, thereby limiting further strength development. Similar trends have been reported in previous studies on high-volume foundry sand incorporation (Siddique *et al.* 2009).

**Fig. 11: Graphical representation of the 7-day and 28-day compressive strengths of control and WFS-SF concrete mixes**

3.3 Split Tensile and Flexural Strengths

Similar to compressive strength trends, the mix containing 10% WFS exhibited superior tensile and flexural performance, which can be attributed to improved interfacial transition zone (ITZ) characteristics resulting from the combined effects of WFS and SF. The angular morphology and rough surface texture of WFS particles promote stronger mechanical interlocking with the surrounding cement paste, delaying crack initiation and propagation, while silica fume contributes to secondary C-S-H formation that densifies the ITZ. However, at higher WFS replacement levels, a reduction in tensile and flexural strengths was observed, which may be associated with excessive fines content and increased particle surface area, potentially leading to less efficient particle packing and localized weak zones within the cementitious matrix.

Split tensile and flexural strength results are presented in Table 6, while the comparative trends are illustrated in Fig. 12.

Table 6. Split tensile and flexural strengths of concrete mixes at 28 days

Mix Type	Split Tensile Strength (MPa)	Flexural Strength (MPa)
Conventional	2.30	9.87
Trial Mix 1	2.82	10.13
Trial Mix 2	2.59	9.73
Trial Mix 3	2.46	8.93

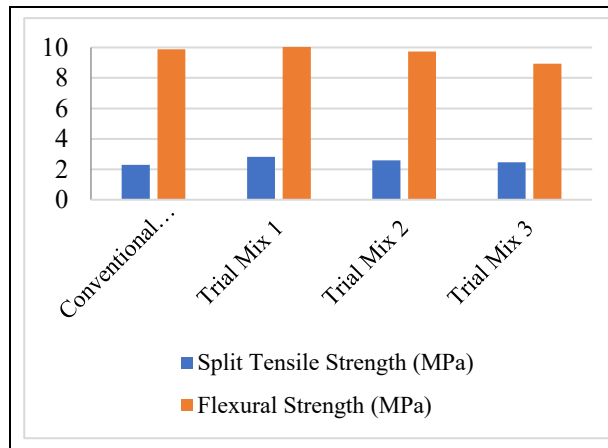


Fig. 12: Graphical representation of split tensile and flexural strengths of concrete mixes at 28 days

3.4 Carbonation Resistance

Carbonation depth measurements obtained at 28 and 450 days are presented in Table 7. No measurable carbonation penetration was detected in any of the investigated mixtures at 28 days, indicating negligible carbonation progression during the early exposure period under the adopted natural exposure conditions.

After 450 days of exposure, measurable carbonation depths were observed, allowing differentiation among the mixtures. The conventional concrete exhibited the highest carbonation depth of 2.5 mm, whereas the concrete containing 10% WFS and 7% SF showed no measurable carbonation penetration within the resolution of the adopted test method. The mixtures incorporating 20% and 30% WFS recorded carbonation depths of 1 mm, indicating improved resistance compared with the control mix.

Table 7. Carbonation resistance of concrete mixes

Mix type	Carbonation depth at 28 days (mm)	Carbonation depth at 450 days (mm)
Conventional	0	2.5
Trial Mix 1	0	0
Trial Mix 2	0	1
Trial Mix 3	0	1

The enhanced carbonation resistance of the modified mixtures is consistent with the denser microstructure observed in SEM analysis and the refined matrix characteristics discussed in Section 3.5. The superior performance of the 10% WFS mixture further supports its identification as the optimum replacement level among the investigated mixtures. Carbonation depth increased slightly at higher WFS contents, suggesting that beyond the optimum replacement level, the beneficial filler effect of WFS may be reduced due to

excessive fines causing increased water demand and reduced packing efficiency.

Overall, the results indicate that the incorporation of WFS and SF can improve carbonation resistance when used at appropriate replacement levels.

3.5 Microstructural and Elemental Analysis

Scanning Electron Microscopy (SEM) observations of the control concrete revealed a relatively heterogeneous microstructure characterized by discontinuous calcium silicate hydrate (C–S–H) gel, plate-like calcium hydroxide (CH) crystals, and interconnected capillary pores within the cement matrix. These features were particularly prominent in the interfacial transition zone (ITZ) surrounding coarse aggregates. The presence of loosely packed hydration products and localized CH accumulation in this region indicates a relatively weak aggregate–paste interface, which is commonly observed in conventional cement-based systems (Fig. 13).

In contrast, the optimized concrete mixture incorporating 10% WFS and 7% SF exhibited a significantly denser and more homogeneous microstructure (Fig. 14). SEM images showed a compact matrix dominated by well-developed C–S–H gel and a noticeably refined pore structure. The interfacial transition zone appeared substantially improved, with hydration products forming a more continuous and tightly bonded phase across the aggregate–paste boundary. Correspondingly, EDS analysis revealed a relative reduction in calcium-rich phases and an increase in silica- and alumina-bearing compounds, indicating the effective pozzolanic reaction between silica fume and calcium hydroxide, leading to the formation of additional C–S–H and calcium aluminosilicate hydrate (C–A–S–H) phases.

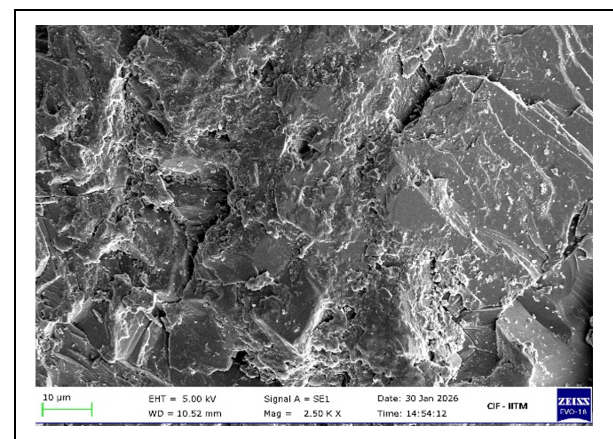


Fig. 13: SEM micrograph of reference concrete (0% WFS) showing porous cement matrix, abundant portlandite crystals, and weak ITZ

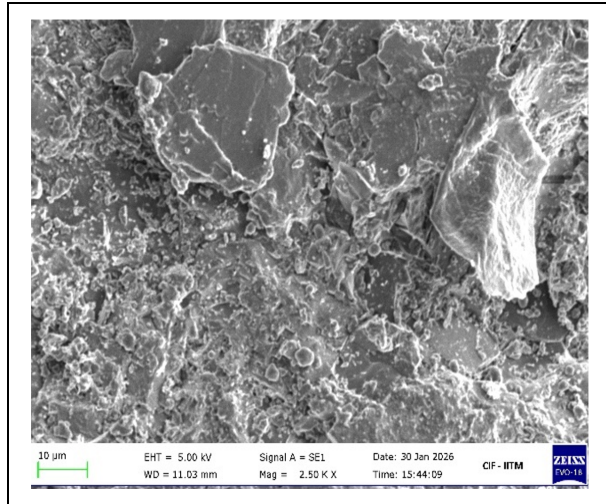


Fig. 14: SEM micrograph of optimized concrete with dense C–S–H formation, refined pore structure, and improved ITZ

The improved performance of the optimized mixture can be attributed to a combined physical and chemical densification mechanism of WFS and SF. The fine particles of waste foundry sand contribute to improved particle packing, filling micro-voids, and reducing capillary porosity. Simultaneously, silica fume participates in pozzolanic reactions that consume calcium hydroxide and generate secondary binding phases, thereby strengthening the cementitious matrix.

The combined physical filling effect of WFS and the pozzolanic reactivity of SF significantly reduce pore connectivity and enhance the integrity of the ITZ. This microstructural refinement correlates well with the experimentally observed improvements in compressive, tensile, and flexural strengths, as well as enhanced resistance to early-age carbonation. These findings suggest that the improved mechanical and durability performance of the modified concrete is primarily governed by microstructural densification and ITZ strengthening rather than mere aggregate substitution.

EDS analysis provided quantitative evidence of compositional modification in the optimized WFS–SF concrete matrix. Compared with the reference concrete (Fig. 15), the optimized mixture (Fig. 16) exhibited a reduction in calcium atomic content from 0.61% to 0.50% and a corresponding decrease in the estimated Ca/Si atomic ratio from 0.028 to 0.025, indicating reduced calcium-rich phases and enhanced silica utilization within the hydrated matrix. Simultaneously, aluminum content increased from 5.38% to 6.81%, suggesting increased formation of aluminosilicate hydration products, likely in the form of secondary C–A–S–H phases (Tables 8 and 9). These compositional changes support the occurrence of pozzolanic reactions between silica fume and calcium hydroxide, leading to

consumption of portlandite and generation of additional binding phases.

Even though quantitative pore size distribution analysis was not performed, the observed reduction in visible pore connectivity and the densification of the cement matrix in the SEM micrograph qualitatively corroborate the enhanced hydration and microstructural refinement of the optimized mixture.

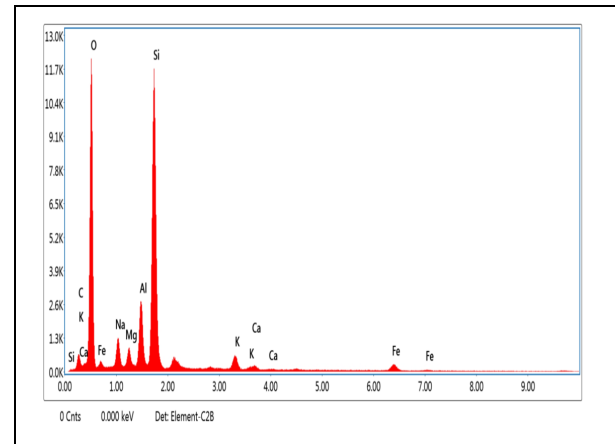


Fig. 15: EDS spectrum of reference concrete indicating elemental composition of the cementitious matrix

Table 8. Comparative SEM–EDS-based microstructural characteristics of reference concrete and optimized concrete

Feature	Conventional Mix	WFS 10% + SF 7%
Matrix density	Heterogeneous, porous	Dense, compact
CH crystals	Abundant, plate-like	Significantly reduced
C–S–H	Discontinuous	Continuous and compact
ITZ	Porous, weak	Dense and refined
Capillary pores	Clearly visible	Largely filled/refined
Microcracks	Present	Minimal/absent

Table 9. Quantitative comparison of EDS-derived atomic elemental composition of reference concrete and optimized concrete

Element	WFS 0% (Reference)	WFS 10% + SF 7%	Trend
Ca	0.61	0.50	↓ Reduced
Si	21.58	19.66	↓ Slight
Al	5.38	6.81	↑ Increased
Fe	1.96	0.38	↓ Reduced

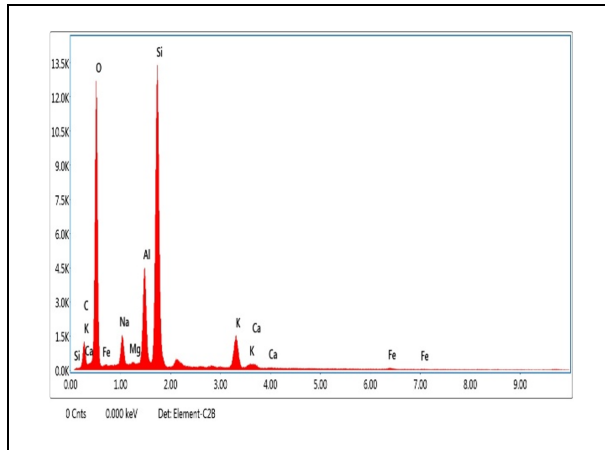


Fig. 16: EDS spectrum of optimized concrete (10% WFS, 7% SF) indicating silica- and alumina-rich phases and reduced calcium content

3.6 Life Cycle Assessment Results

LCA results indicate that the partial replacement of conventional concrete constituents with WFS and SF provides measurable environmental advantages across several impact categories (Table 10). Fig. 17 presents the normalized environmental impacts of the investigated mixtures relative to the reference concrete. For comparative visualization, the environmental impact results were normalized relative to the conventional concrete mixture, which was assigned a baseline value of 1.0 for each impact category. No weighting factors were applied, as the purpose of normalization was only to facilitate direct comparison of the environmental performance of the investigated mixtures without introducing subjective weighting assumptions.

The incorporation of WFS and SF reduced the climate change potential by approximately 6.1–7.4% compared with the control mixture. This improvement is mainly associated with the reduction in cement consumption through silica fume substitution and the decreased demand for natural fine aggregates through the use of WFS. As cement production is the primary contributor to the embodied carbon of concrete, even moderate reductions in cement content can produce noticeable reductions in overall greenhouse gas emissions.

Similarly, fossil resource consumption decreased by 5.3–7.7%, reflecting the lower energy demand associated with reduced cement manufacturing and aggregate extraction. Land use impacts also showed a substantial reduction, ranging from 8.5% to 23.0%, which highlights the environmental advantage of replacing natural sand with industrial by-products such as waste foundry sand. These reductions indicate that WFS utilization can contribute to minimizing the environmental disturbance associated with natural aggregate mining.

Among the investigated mixtures, the concrete containing 10% WFS and 7% SF provided the most balanced performance when both environmental and mechanical aspects were considered. Although mixtures with higher WFS content showed slightly greater environmental reductions, the associated improvements in mechanical strength were less pronounced. Therefore, the optimized mixture represents a suitable compromise between structural performance and environmental sustainability.

Sensitivity analysis indicated that reasonable variations in transportation distance exert only a minor influence on comparative climate change impacts, suggesting that the observed environmental benefits are primarily governed by material substitution effects rather than transportation assumptions.

The observed reductions are consistent with previously reported environmental benefits for sustainable concrete mixtures incorporating supplementary cementitious materials and recycled fine aggregates. For example, Lei *et al.* (2022) reported 5.6–6.1% embodied carbon reduction for recycled fine aggregate concrete, Anh *et al.* (2023) observed approximately 9.5% reduction in global warming potential with 10% supplementary cementitious material substitution, and Chen *et al.* (2019) reported 11–19% greenhouse gas reduction for fly ash/slag-based concrete systems at higher replacement levels. These comparisons indicate that the environmental improvements obtained in the present study fall within the practical range commonly reported in the literature, thereby supporting the validity of the present LCA outcomes.

Table 10. Life cycle environmental impact results for conventional concrete and WFS-SF concrete (functional unit: 1 m³ of concrete)

Impact Category	Conventional	Trial Mix 1	Trial Mix 2	Trial Mix 3	Unit
Climate Change	384.43	361.00	358.37	355.92	kg CO ₂ -eq./m ³
Resource Use	2957.16	2799.68	2764.68	2729.69	MJ/m ³
Human Toxicity	9.80 × 10 ⁻⁸	9.27 × 10 ⁻⁸	9.10 × 10 ⁻⁸	8.92 × 10 ⁻⁸	CTUh/m ³
Land Use	8679.01	7944.09	7314.16	6684.24	pt/m ³
Water Use	21.87	21.00	21.00	20.82	m ³ /m ³

The cradle-to-gate system boundary adopted in this study enables consistent comparison among mixtures while capturing the dominant environmental burdens associated with raw material production and processing.

Overall, the findings confirm that controlled incorporation of WFS and SF can reduce the environmental footprint of concrete while maintaining satisfactory mechanical performance. From a circular

economy perspective, reutilization of foundry by-products diverts industrial waste from landfill while conserving natural aggregate resources. Given the scale of global concrete production, even modest substitution levels may yield substantial cumulative environmental benefits.

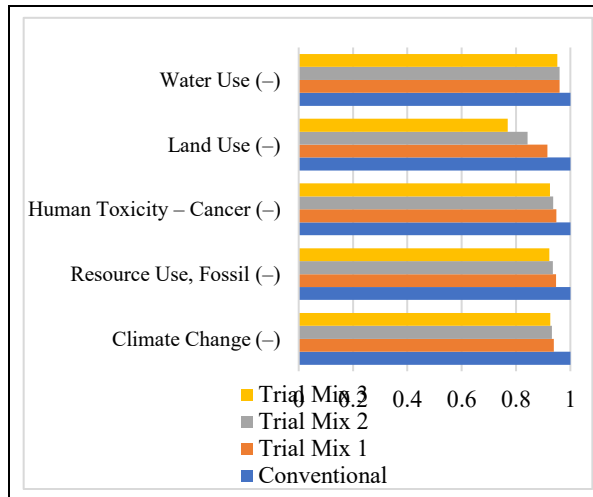


Fig. 17: Normalized life cycle environmental impact categories for conventional concrete and WFS-SF concrete mixtures, expressed relative to the conventional concrete baseline (normalized to 1.0)

3.7 Strength-Environment Optimization

A critical observation emerges from the strength-environment optimization analysis of the investigated mixtures. Although the maximum environmental benefit was obtained at 30% WFS, corresponding to a 23% reduction in land use impact, the mechanical performance indicated a more favorable balance at 10% WFS replacement.

The mixture containing 10% WFS and 7% SF demonstrated the most balanced performance in terms of structural efficiency and environmental improvement. The measured properties of this optimized mix include:

- Compressive strength: 37.2% increase relative to conventional concrete
- Split tensile strength: 22.6% increase relative to conventional concrete
- Climate change impact: 6.09% reduction
- Land use impact: 8.47% reduction

Although higher WFS replacement levels provide greater environmental reductions, the corresponding mechanical performance does not improve proportionally. The optimized mixture, therefore, represents an effective compromise between structural performance and environmental sustainability.

Overall, the 10% WFS + 7% SF mixture achieved a normalized environmental performance score of 56.4% relative to the maximum environmental benefit observed among the investigated mixtures, while simultaneously providing superior mechanical properties. This indicates that the mixture offers the most balanced compromise between environmental improvement and structural performance for practical concrete applications.

4. CONCLUSION

This study evaluated the synergistic incorporation of waste foundry sand and silica fume in M40 concrete through an integrated assessment of mechanical performance, early-age carbonation behavior, microstructural characteristics, and cradle-to-gate environmental impacts. The combined experimental-microstructural-LCA framework adopted in this study provides a comprehensive basis for evaluating the structural and sustainability performance of WFS-SF-modified concrete.

Among the mixtures investigated, the concrete containing 10% WFS and 7% SF exhibited the most favorable overall performance. This mixture achieved increases of 37.2% in compressive strength, 22.6% in split tensile strength, and 2.6% in flexural strength compared with the conventional concrete, indicating that moderate WFS replacement combined with silica fume can enhance the structural performance of concrete.

Carbonation testing indicated no measurable carbonation at 28 days for all mixtures under natural exposure conditions. After 450 days, the optimized mixture continued to exhibit superior carbonation resistance, showing no measurable carbonation depth, whereas the conventional concrete recorded a carbonation depth of 2.5 mm. These results suggest enhanced long-term carbonation resistance of the optimized mixture under the investigated exposure conditions.

Life cycle assessment showed that the incorporation of WFS and SF reduced the environmental burdens of concrete production, with climate change potential decreasing by 6.1–7.4%, fossil resource use by 5.3–7.7%, and land use by 8.5–23.0% relative to conventional concrete. These reductions confirm the environmental advantages of partially replacing cement and natural fine aggregate with industrial by-products.

Although higher WFS replacement levels yielded slightly greater environmental reductions, the 10% WFS + 7% SF mixture provided the best balance between structural performance and environmental efficiency, making it the optimum mixture among those investigated for practical structural concrete applications.

The results demonstrate that controlled incorporation of WFS and SF can support sustainable concrete production through simultaneous enhancement of engineering performance and reduction of environmental impact. However, the findings are limited to the specific WFS source, exposure conditions, and cradle-to-gate LCA scope considered in this study.

Future work could investigate the source-dependent variability of WFS, long-term durability under aggressive exposure environments, and cradle-to-grave life cycle performance to further validate the practical implementation potential of WFS–SF concrete.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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