Integrated Structural Performance and Carbon Footprint Assessment of Reinforced Concrete Incorporating Supplementary Cementitious Material with Multiple Cement Sources

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ABSTRACT

The environmental impact associated with Ordinary Portland Cement (OPC) production necessitates the development of sustainable concrete materials that maintain structural performance while reducing carbon emissions. Supplementary cementitious materials (SCMs) such as Metakaolin, Alccofine, and Biocement have demonstrated potential for improving concrete properties; however, comprehensive studies integrating structural behavior, durability performance, microstructural characteristics, and environmental assessment across multiple cement sources remain limited. This study presents an experimental and analytical investigation on the mechanical properties, durability, flexural behavior, microstructural characteristics, and carbon footprint of reinforced concrete incorporating SCMs as partial replacements for OPC at replacement levels of 5%, 10%, and 15%. Concrete mixes of grades M25–M75 were evaluated through compressive strength, split tensile strength, and modulus of elasticity tests, while structural performance was assessed using flexural testing of reinforced concrete beams under two-point loading conditions. Durability performance was examined through water absorption and carbonation resistance tests, and microstructural characterization was conducted using Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Analysis (EDX), and Thermogravimetric Analysis (TGA). A cradle-to-gate Life Cycle Assessment (LCA) was performed using OpenLCA in accordance with ISO 14040 and ISO 14044 standards to quantify embodied carbon emissions. Results indicated that Alccofine-based concrete achieved higher compressive strength (28.2 MPa), lower water absorption (0.565%), and approximately 35–40% greater load-carrying capacity compared to Metakaolin-based concrete, while increasing SCM replacement levels resulted in consistent reductions in CO_2 emissions across all concrete grades. The study establishes an integrated performance–environment framework for the development of sustainable and high-performance reinforced concrete suitable for modern construction applications.

Keywords: Supplementary cementitious materials; Reinforced concrete; Flexural behavior; Durability; Life cycle assessment; Carbon footprint; Sustainable concrete.

1. INTRODUCTION

The construction industry relies heavily on concrete, and the production of Ordinary Portland Cement (OPC) is associated with significant carbon dioxide (CO_2) emissions and energy consumption. Reducing the environmental impact of concrete while maintaining structural performance has therefore become an important objective in sustainable construction. One effective approach is the use of supplementary cementitious materials (SCMs) such as Metakaolin, Alccofine, and Biocement as partial replacements for cement.

These materials can improve strength, durability, and microstructural properties of concrete by enhancing hydration reactions and refining pore structure. In addition, the incorporation of SCMs reduces clinker content, thereby lowering the carbon footprint of concrete production. Evaluating both performance and environmental impact is essential for identifying optimal material combinations for modern infrastructure.

Therefore, this study investigates the mechanical properties, flexural behavior, durability performance, microstructural characteristics, and carbon footprint of reinforced concrete incorporating Metakaolin, Alccofine, and Biocement at replacement levels of 5%, 10%, and 15%.

1.1 OBJECTIVES

- To develop concrete mixes incorporating Metakaolin, Alccofine, and Biocement at replacement levels of 5%, 10%, and 15% and evaluate their influence on mechanical properties.
- To investigate the flexural behavior and load–deflection response of reinforced concrete beams prepared with selected SCM-based mixes under two-point loading conditions.
- To assess the durability performance of SCM-based concrete through water absorption and carbonation resistance tests.
- To analyze the microstructural characteristics of optimized concrete mixes using Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Analysis (EDX), and Thermogravimetric Analysis (TGA).

- To quantify the carbon footprint of concrete mixes using a cradle-to-gate Life Cycle Assessment (LCA) approach implemented in OpenLCA in accordance with ISO 14040 and ISO 14044 standards.
- To identify an optimal SCM-based concrete mix that achieves a balance between structural performance, durability, and reduction in carbon emissions for sustainable construction applications.

2. MATERIALS

The materials used in this study included Ordinary Portland Cement (OPC), supplementary cementitious materials (SCMs), fine aggregate, coarse aggregate, water, and chemical admixture. All materials were selected in accordance with relevant Indian Standard specifications to ensure consistency and reliability of experimental results.

2.1 CEMENT

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:2013 was used as the primary binder material. Multiple cement sources were considered to evaluate the influence of cement variability on concrete performance and carbon emissions. The physical properties of cement, including specific gravity, fineness, and initial and final setting times, were determined using standard laboratory procedures.

2.2 SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCMS)

Three supplementary cementitious materials were used as partial replacements for cement:

- **Metakaolin (MK)** — a highly reactive pozzolanic material known for improving strength and durability.
- **Alccofine (AF)** — an ultrafine slag-based material that enhances particle packing and early strength development.
- **Biocement (BC)** — an eco-friendly binder material used to reduce the environmental impact of concrete production.

These materials were incorporated at replacement levels of 5%, 10%, and 15% by weight of cement. The physical and chemical properties of the SCMs were determined as per relevant standards.

2.3 FINE AGGREGATE

Natural river sand conforming to Zone II grading as per IS 383:2016 was used as fine aggregate. The sand was clean, free from organic impurities, and possessed suitable grading characteristics. The specific gravity and fineness modulus were determined using standard test methods.

2.4 COARSE AGGREGATE

Crushed granite aggregate with a nominal maximum size of 20 mm was used as coarse aggregate. The aggregate satisfied the requirements of IS 383:2016. The physical properties, including specific gravity, water absorption, and bulk density, were determined prior to use.

2.5 WATER

Potable water free from harmful impurities was used for mixing and curing of concrete. The water satisfied the requirements of IS 456:2000.

3. MIX DESIGN

Concrete mixes of grade M25 were prepared using Ordinary Portland Cement (OPC) with partial replacement by Bio cement, Alccofine, and Metakaolin at replacement levels of 5%, 10%, and 15%. A constant water–binder ratio of 0.41 was maintained for all mixes to ensure uniform workability and consistency.

The detailed mix proportions of cement, aggregates, binder materials, and water used in the experimental program are presented in Table 1.

Table 1 : Mix Design

MIX ID	BINDER %	BINDER NAME	CEMENT	COARSE AGGREGATE	FINE AGGREGATE	BINDER	WATER
M1	100	OPC	342	1161	742	0	154
M2	5	BIO CEMENT	325	1161	742	17	154
M3	10	BIO CEMENT	308	1161	742	34	154
M4	15	BIO CEMENT	291	1161	742	51	154
M5	5	ALCOFINE	325	1161	742	17	154

M6	10	ALCOFINE	308	1161	742	34	154
M7	15	ALCOFINE	291	1161	742	51	154
M8	5	METAKOILIN	325	1161	742	17	154
M9	10	METAKOILIN	308	1161	742	34	154
M10	15	METAKOILIN	291	1161	742	51	154

4. MATERIAL TESTING

Material testing was conducted to determine the physical and chemical properties of aggregates and cement used in the concrete mixes. These properties are essential for ensuring the quality, performance, and environmental assessment of concrete materials. Standard laboratory procedures were followed to evaluate the suitability of the materials for concrete production.

4.1 SPECIFIC GRAVITY OF AGGREGATES

Specific gravity is a fundamental property used in concrete mix design, representing the ratio of the mass of aggregates to the mass of an equal volume of water. In this study, the specific gravity of fine and coarse aggregates was determined using the pycnometer method under oven-dry conditions in accordance with relevant standard procedures to eliminate moisture effects.

The measured specific gravity values were 2.69 for fine aggregate and 2.56 for coarse aggregate**,** indicating that both materials fall within the acceptable range for concrete production and are suitable for mix proportioning in structural concrete.

4.2 DETERMINATION OF CO_2 CONTENT IN CEMENT

The carbon dioxide (CO_2) content of cement samples obtained from different sources was determined using the muffle furnace method to evaluate variations in potential carbon release associated with cement composition. Approximately 2 g of cement sample was first heated at 450°C to remove chemically bound water, followed by further heating at 900°C until a constant mass was achieved to ensure complete decomposition of carbonates.

The loss in mass between the two temperature stages was used to estimate the CO_2 content of the cement samples. The results indicated variation among cement sources, with sample S2 exhibiting a higher CO_2 content of 0.32% compared to 0.17% for sample S1**.** These variations reflect differences in carbonate composition and support the environmental assessment by demonstrating the influence of cement characteristics on carbon emissions.

5. MECHANICAL PROPERTIES

The mechanical properties of concrete incorporating supplementary cementitious materials (SCMs) were evaluated through compressive strength, modulus of elasticity, and split tensile strength tests. These parameters are essential for assessing the load-bearing capacity, stiffness, and cracking resistance of concrete used in structural applications.

5.1 COMPRESSIVE STRENGTH

Compressive strength tests were conducted on 150 mm cube specimens in accordance with IS 516:1959. The specimens were tested using a compression testing machine, and load was applied gradually until failure. The compressive strength was calculated as the ratio of the maximum load to the cross-sectional area of the specimen.

Table 5.1: Compressive Strength Results

Mix	7 Days (MPa)	28 Days (MPa)
M25_OPC-53_85_MK_15	19.0	26.0
M25_OPC-53_85_AL_15	21.0	28.2

Both SCM-based mixes achieved satisfactory compressive strength at 28 days. The Alccofine-based mix exhibited higher strength (28.2 MPa) compared to the Metakaolin mix (26.0 MPa), which may be attributed to improved particle packing and enhanced hydration associated with ultrafine materials.

5.2 MODULUS OF ELASTICITY

The modulus of elasticity was determined from the stress–strain response of concrete specimens under controlled loading conditions. The slope of the initial linear portion of the stress–strain curve was used to evaluate the stiffness characteristics of the concrete.

Table 5.2: Modulus of Elasticity

Mix	7 Days (N/mm²)	28 Days (N/mm²)
M25_OPC-53_85_MK_15	20450	25655.48
M25_OPC-53_85_AL_15	11450	13350

The Metakaolin-based mix exhibited higher modulus of elasticity values, indicating improved stiffness and deformation resistance. This behavior may be associated with the formation of a denser microstructure and stronger interfacial transition zone.

5.3 SPLIT TENSILE STRENGTH

Split tensile strength tests were conducted on cylindrical specimens (150 mm × 300 mm) in accordance with IS 5816:1999. The load was applied diametrically until failure to evaluate the tensile strength and cracking resistance of the concrete.

Table 5.3: Split Tensile Strength Results

Mix	7 Days (MPa)	28 Days (MPa)
M25_OPC-53_85_MK_15	4.65	7.23
M25_OPC-53_85_AL_15	6.35	7.53

The results indicate that both mixes achieved adequate tensile strength at 28 days. The Alccofine-based mix exhibited slightly higher tensile strength (7.53 MPa) compared to the Metakaolin mix (7.23 MPa), suggesting improved resistance to crack initiation and propagation.

6. FLEXURAL BEHAVIOUR OF REINFORCED CONCRETE BEAMS

The flexural performance of reinforced concrete beams incorporating Metakaolin (MK–15) and Alccofine (AL–15) mixes was evaluated under two-point loading conditions. The load–deflection response, crack initiation, and failure characteristics were analyzed to assess the structural behavior and ductility of the developed concrete mixes.

Fig. 1: Flexural Testing of Reinforced Concrete Beam with M25 MK–15 Mix

The MK–15 beam exhibited nearly linear behavior during the initial stages of loading, followed by a rapid increase in deflection with increasing load. Crack initiation occurred at approximately 4 tons, after which cracks propagated quickly, leading to significant mid-span deflection. The ultimate load-carrying capacity of the beam was observed to be 5.2 tons. Failure was governed primarily by flexural cracking at the mid-span, indicating relatively brittle behavior and lower stiffness characteristics.

Fig. 2: Flexural Testing of Reinforced Concrete Beam with M25 AL–15 Mix

In contrast, the AL–15 beam demonstrated improved structural performance. The beam exhibited linear elastic behavior at early loading stages with comparatively lower deflection, indicating higher stiffness. Crack initiation occurred slightly later at around 4.2 tons, reflecting enhanced resistance to crack formation. With further loading, the beam maintained controlled deformation and delayed crack propagation. The ultimate load-carrying capacity reached 7.1 tons, which is significantly higher than that of the MK–15 beam. Failure occurred due to compression at the top fiber, accompanied by crushing and localized spalling near the support region, indicating a more ductile structural response.

Table 6.1: Load–Deflection Behaviour of Reinforced Concrete Beams

Load (Ton)	MK–15 (L/2 mm)	MK–15 (L/3 mm)	AL–15 (L/2 mm)	AL–15 (L/3 mm)
0.0	0.00	0.00	0.00	0.00
1.0	0.85	0.30	0.40	0.40
2.0	3.08	1.50	1.95	1.55
3.0	5.25	3.60	3.40	2.78
4.0	7.50	5.20	4.90	4.04
5.0	9.17	6.80	5.70	5.70
Ultimate	13.50	8.00	10.55	9.70

Overall, the AL–15 beam demonstrated superior flexural performance, with approximately 35–40% higher load-carrying capacity compared to the MK–15 beam. The improved behavior is attributed to enhanced particle packing, improved bonding characteristics, and increased matrix densification associated with ultrafine materials, resulting in increased stiffness, delayed crack propagation, and improved ductility. In contrast, the MK–15 beam exhibited higher deflection and earlier crack propagation, indicating relatively lower structural efficiency.

7. MICROSTRUCTURAL CHARACTERIZATION

The microstructural characteristics of M25 concrete mixes incorporating Alccofine (AL–15) and Metakaolin (MK–15) were examined to understand hydration behavior, pore structure, and interfacial bonding mechanisms. Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX) analyses were performed to evaluate the morphology and elemental composition of the hydrated cement matrix.

7.1 SCANNING ELECTRON MICROSCOPY (SEM)

SEM analysis was conducted to examine the microstructural features and distribution of hydration products in the concrete matrix.

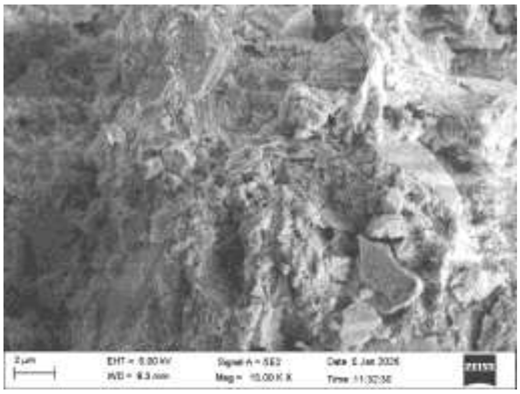

Fig. 3: SEM Image of M25 AL–15 Mix

The SEM image of the AL–15 mix reveals a dense and well-compacted microstructure characterized by the presence of gel-like hydration products, primarily calcium silicate hydrate (C–S–H). The matrix exhibits a refined pore structure with uniformly distributed fine pores and minimal microcracks. This observation indicates effective hydration and enhanced packing density associated with the ultrafine particle size of Alccofine. Furthermore, the interfacial transition zone (ITZ) appears dense and continuous, suggesting improved particle–matrix bonding, which contributes to enhanced strength and durability performance.

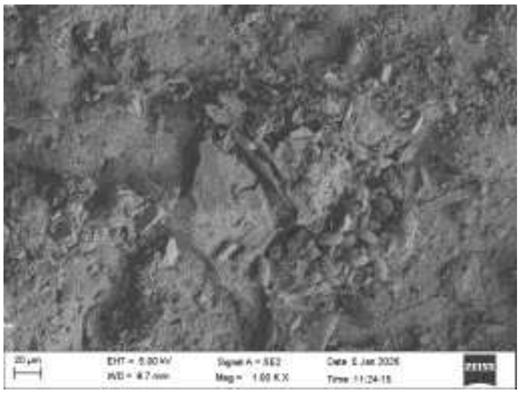

Fig. 4: SEM Image of M25 MK–15 Mix

The SEM image of the MK–15 mix shows comparatively larger and irregular voids within the matrix. The observed oval-shaped features represent air voids or capillary pores, appearing darker due to the absence of solid material. These voids may result from entrapped air during compaction or microstructural variations during sample preparation. The microstructure appears relatively less dense, with localized discontinuities, indicating comparatively weaker packing and higher porosity than the AL–15 mix.

7.2 ENERGY DISPERSIVE X-RAY SPECTROSCOPY (EDX)

EDX analysis was performed to determine the elemental composition of the concrete matrix and to identify the chemical phases associated with hydration products.

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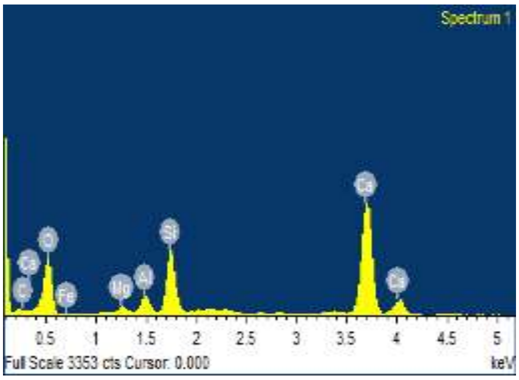


Fig. 5: EDX Spectrum of M25 AL–15 Mix

Table 7.1: Elemental Composition of AL–15 Mix

Element	Weight %	Atomic %
C	6.92	11.44
O	53.58	66.55
Mg	0.96	0.78
Al	2.45	1.80
Si	8.97	6.35
Ca	24.49	12.14
Fe	2.64	0.94

The AL–15 mix shows a high concentration of calcium and oxygen, indicating the dominance of calcium-based hydration products such as calcium silicate hydrate (C–S–H) and calcium hydroxide. The presence of silicon and aluminium confirms the formation of calcium–alumino–silicate phases, which contribute to improved strength and durability. Minor elements such as magnesium and iron are present as trace constituents, while carbon may be associated with carbonation or sample preparation effects.

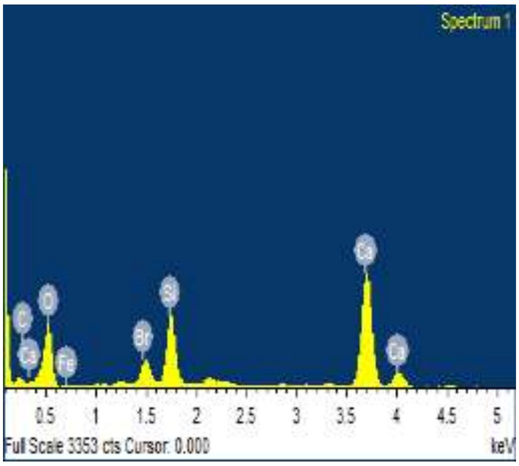


Fig. 6: EDX Spectrum of M25 MK–15 Mix

Table 7.2: Elemental Composition of MK–15 Mix

Element	Weight %	Atomic %
C	10.88	17.91
O	51.10	63.17
Si	8.97	6.32
Ca	21.28	10.50
Fe	1.62	0.57
Br	6.15	1.52

The MK–15 mix is characterized by the presence of calcium, oxygen, and silicon, indicating a calcium–silicate-based matrix. The relatively higher silicon content highlights the pozzolanic nature of Metakaolin. The presence of bromine may be attributed to minor contamination or residual chemical components during testing. Compared to the AL–15 mix, the calcium content is lower, indicating comparatively reduced formation of dense calcium-rich hydration products.

7.3 COMPARATIVE MICROSTRUCTURAL ANALYSIS

A comparative evaluation of AL–15 and MK–15 mixes highlights significant differences in microstructural characteristics:

- The AL–15 mix exhibits a denser and more homogeneous microstructure with refined pore distribution, contributing to improved mechanical strength and durability performance.
- The MK–15 mix shows relatively higher porosity and a more heterogeneous structure, which may influence its mechanical performance.
- The higher calcium content observed in the AL–15 mix indicates enhanced formation of calcium silicate hydrate (C–S–H) gel, resulting in improved strength development.
- The MK–15 mix demonstrates higher silicate content, reflecting its pozzolanic behavior; however, the overall matrix is comparatively less compact than that of the AL–15 mix.
- The improved interfacial transition zone (ITZ) observed in the AL–15 mix contributes to better bonding characteristics and reduced crack propagation.

7.4 THERMOGRAVIMETRIC ANALYSIS (TGA)

Thermogravimetric analysis (TGA), along with differential scanning calorimetry (DSC) and differential thermal analysis (DTA), was performed to evaluate the thermal stability and decomposition behavior of concrete incorporating supplementary cementitious materials (SCMs). The analysis was conducted to assess the mass loss characteristics associated with moisture evaporation, dehydration of hydration products, and decomposition of calcium-based compounds at elevated temperatures.

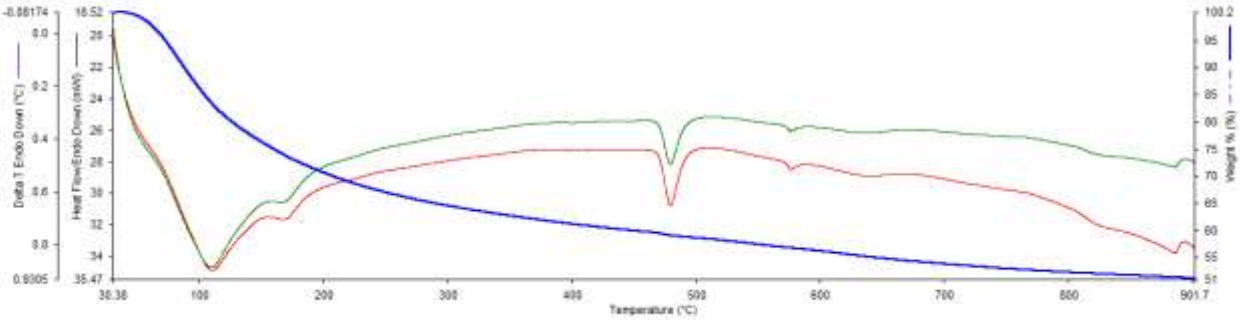


Fig. 7: TGA Curve for M25 – AL–15 Mix

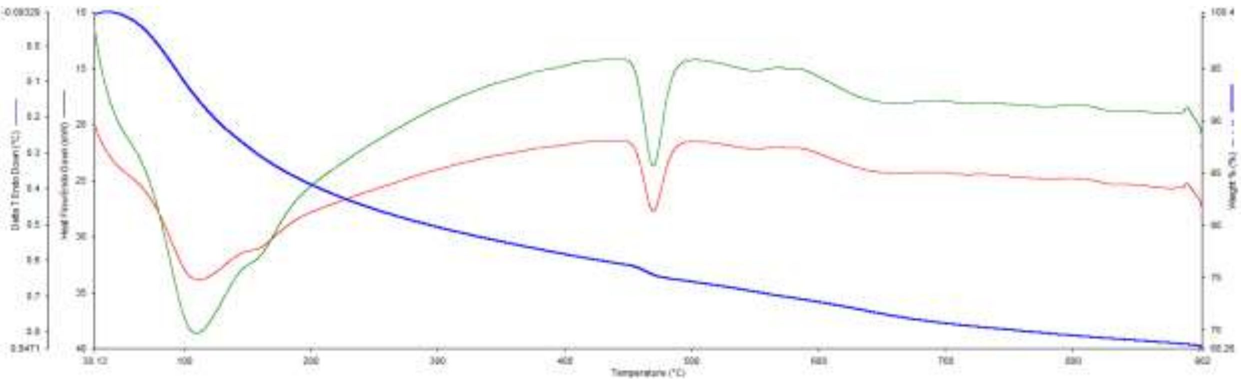


Fig. 8: TGA Curve for M25 – MK–15 Mix

The results indicate that Metakaolin-incorporated concrete (MK–15) exhibits comparatively superior thermal stability compared to Alccofine-modified concrete (AL–15). The MK–15 mix shows relatively lower total mass loss up to 900 °C, which can be attributed to the formation of a denser and more stable microstructure resulting from pozzolanic reactions. The observed weight loss in both mixes is primarily associated with evaporation of free moisture, dehydration of calcium silicate hydrate (C–S–H) gel, and decomposition of calcium carbonate at higher temperatures.

In contrast, the AL–15 mix demonstrates relatively higher mass loss, indicating the presence of greater amounts of physically bound moisture and increased decomposition of hydration products, suggesting comparatively lower thermal resistance under elevated temperature conditions.

The DSC and DTA results further support these observations:

- The MK–15 mix exhibits broader and less intense endothermic peaks, indicating gradual and controlled thermal transitions and improved thermal stability.
- The AL–15 mix shows sharper and more pronounced peaks, particularly around **100 °C** and **500 °C**, corresponding to rapid moisture evaporation and decomposition of calcium hydroxide.

Overall, the results demonstrate that Metakaolin-enhanced concrete exhibits more stable and controlled thermal behavior under elevated temperature exposure, whereas the Alccofine-based mix shows comparatively higher thermal reactivity during heating.

8. DURABILITY PERFORMANCE

Durability tests were conducted to evaluate the resistance of concrete mixes to moisture ingress and carbonation. These parameters are essential for assessing the long-term performance and service life of reinforced concrete structures incorporating supplementary cementitious materials (SCMs).

8.1 WATER ABSORPTION TEST

The water absorption test was conducted to assess the permeability characteristics of the concrete mixes. Lower water absorption indicates reduced porosity and improved resistance to moisture penetration.

The results show that the Metakaolin mix (MK–15) recorded an average water absorption of **0.637%**, while the Alccofine mix (AL–15) recorded a lower value of **0.565%**. The reduced water absorption observed in the Alccofine mix indicates a denser microstructure and improved pore refinement, resulting in enhanced durability and resistance to moisture ingress.

Table 8.1: Water Absorption Results for MK–15 Mix

Sample	Water Absorption (%)	Average (%)
1	0.557	0.637
2	0.732	
3	0.623	

Table 8.2: Water Absorption Results for AL–15 Mix

Sample	Water Absorption (%)	Average (%)
1	0.595	0.565
2	0.587	
3	0.515	

8.2 CARBONATION TEST

The carbonation resistance of the concrete was evaluated using the phenolphthalein indicator method. After exposure, phenolphthalein solution was applied to the freshly cut surface of the specimens to identify the carbonation depth.

Fig. 9: MK–15 Specimen after Phenolphthalein Test

Fig. 10: AL–15 Specimen after Phenolphthalein Test

Both MK–15 and AL–15 specimens exhibited pink coloration, indicating non-carbonated concrete and the presence of sufficient alkalinity. The measured pH values in both mixes remained above 9.5, confirming adequate protection of reinforcing steel against corrosion.

However, slight differences were observed between the mixes. The Metakaolin concrete (MK–15) showed good carbonation resistance due to pore refinement resulting from pozzolanic reactions. The Alccofine concrete (AL–15) exhibited more uniform and intense pink coloration, indicating a denser matrix and improved alkalinity retention. Owing to its ultrafine particle size and micro-filling effect, the Alccofine mix demonstrated comparatively better resistance to carbonation than the Metakaolin mix.

8.3 ACID ATTACK TEST

The resistance of concrete to acidic environments was evaluated using a hydrochloric acid (HCl) solution. After standard curing, the concrete specimens were immersed in the prepared acid solution for an exposure duration of approximately 69 days. The solution was prepared by mixing 500 mL of hydrochloric acid with 32 liters of water, ensuring complete immersion of the specimens throughout the test period.

After the exposure period, the physical condition of the specimens was visually inspected to assess surface deterioration and durability performance.

Acid Attack Test on MK–15 Sample

The MK–15 specimen exhibited visible surface deterioration after exposure to the acid solution. The surface became rough and slightly porous compared to its original condition, indicating chemical interaction between the acid and cement paste. Minor surface erosion was observed, with localized exposure of aggregates in certain areas. Slight spalling was noticed near the edges and corners, and the surface color changed from grey to a lighter shade due to chemical reaction with the acidic medium. However, no major cracking or structural disintegration was observed, indicating moderate resistance to acid attack.

Acid Attack Test on AL–15 Sample

The AL–15 specimen also showed noticeable changes after exposure to the hydrochloric acid solution. The surface became rough and uneven, and slight rounding of edges and corners was observed due to gradual material loss. A localized cavity was detected on one face of the specimen, suggesting surface deterioration caused by acid penetration. Although the specimen maintained its overall structural integrity, the surface strength and durability were reduced after prolonged exposure.

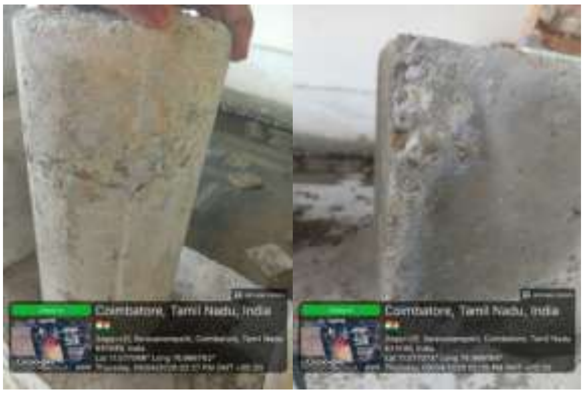


Fig. 11: Acid Attack Test Specimens after Exposure

Fig. 12: Sulphate Attack Test Specimens after Exposure

Overall, both mixes were affected by the acidic environment; however, the AL–15 specimen exhibited comparatively higher surface deterioration, indicating slightly lower resistance to acid attack compared to the MK–15 mix.

8.4 SULPHATE ATTACK TEST

The sulphate resistance of concrete was evaluated by immersing specimens in a 2% sodium sulphate (Na_2SO_4) solution prepared by dissolving 500 g of sodium sulphate in 25 liters of water. The specimens were exposed to the sulphate solution for approximately 30 days under controlled laboratory conditions.After the exposure period, the specimens were visually inspected to assess surface condition, cracking behavior, and overall durability.

Sulphate Attack Test on MK–15 Sample

The MK–15 specimen exhibited slight surface roughness and minor whitish deposits after exposure to the sulphate solution. These deposits indicate limited sulphate interaction with the cement matrix. No significant cracking, spalling, or disintegration was observed, and the edges and corners remained intact. These observations suggest that the Metakaolin-based concrete demonstrated good resistance to sulphate attack under the given test conditions.

Sulphate Attack Test on AL–15 Sample

The AL–15 specimen showed only minor surface roughness and slight discoloration after exposure to the sulphate solution. No major cracks, scaling, or structural disintegration were observed. The aggregates remained well bonded to the cement matrix, and the overall structural integrity of the specimen was maintained. The limited surface deterioration indicates effective resistance to sulphate attack.

A comparison between the two mixes indicates that both MK–15 and AL–15 specimens demonstrated satisfactory resistance to sulphate attack. However, the AL–15 mix exhibited slightly lower surface deterioration, suggesting comparatively better resistance to sulphate-induced damage under the same exposure conditions.

9. LIFE CYCLE ASSESSMENT (LCA)

Life Cycle Assessment (LCA) was conducted to evaluate the environmental impact associated with the production of concrete incorporating supplementary cementitious materials (SCMs). The assessment was performed in accordance with ISO 14040 and ISO 14044 standards using a cradle-to-gate approach. The objective of the analysis was to quantify carbon dioxide (CO_2) emissions associated with different concrete mixes and to identify low-carbon material combinations suitable for sustainable construction.

9.1 LCA FRAMEWORK

The LCA methodology adopted in this study consists of four major phases:

- **Goal and Scope Definition:** The primary objective was to quantify the CO_2 emissions of concrete mixes prepared with different cement sources and SCM replacement levels. The functional unit selected for the analysis was 1 m^3 of concrete, and a cradle-to-gate system boundary was defined.
- **Life Cycle Inventory (LCI):** Inventory data were collected for raw materials, fuel consumption, electricity usage, and transportation associated with clinker production, cement manufacturing, and concrete production.
- **Life Cycle Impact Assessment (LCIA):** The IPCC 2021 Global Warming Potential (GWP100) method was used to quantify greenhouse gas emissions in terms of carbon dioxide equivalent (CO_2-eq).
- **Interpretation:** The results were analyzed to identify major emission sources and to determine the optimal mix combinations that minimize environmental impact while maintaining structural performance.

9.2 SYSTEM BOUNDARY

A cradle-to-gate system boundary was adopted for the environmental assessment, covering the following stages:

- Raw material extraction
- Clinker and cement production
- Transportation of materials
- Concrete manufacturing

Among these stages, clinker production was identified as the dominant contributor to CO_2 emissions due to the calcination of limestone and fuel combustion during kiln operation.

9.3 LIFE CYCLE INVENTORY AND EMISSION FACTORS

The life cycle inventory analysis revealed the following key emission factors:

- **Clinker emission:** approximately 909 kg CO_2/ton
- **Gypsum emission:** approximately 139 kg CO_2/ton

Emission factors were obtained from established life cycle databases for:

- Supplementary cementitious materials (Metakaolin, Alccofine, Biocement)
- Construction materials (aggregates, water, and admixtures)
- Transportation and energy consumption

Among all materials, cement exhibited the highest emission factor, ranging from approximately 0.85–0.87 kg CO_2/kg, while supplementary cementitious materials demonstrated comparatively lower emission values due to reduced clinker content and utilization of industrial by-products.

9.4 OPENLCA MODELLING

The LCA model was developed using OpenLCA software to simulate the environmental impact of concrete production. The modelling process included the following steps:

- Definition of material and energy flows
- Creation of unit processes for concrete production
- Integration of datasets from standard life cycle databases
- Development of a product system representing 1 m^3 of concrete

The IPCC 2021 GWP100 method was used for impact assessment, and contribution analysis was performed to identify major emission sources and environmental hotspots within the production system.

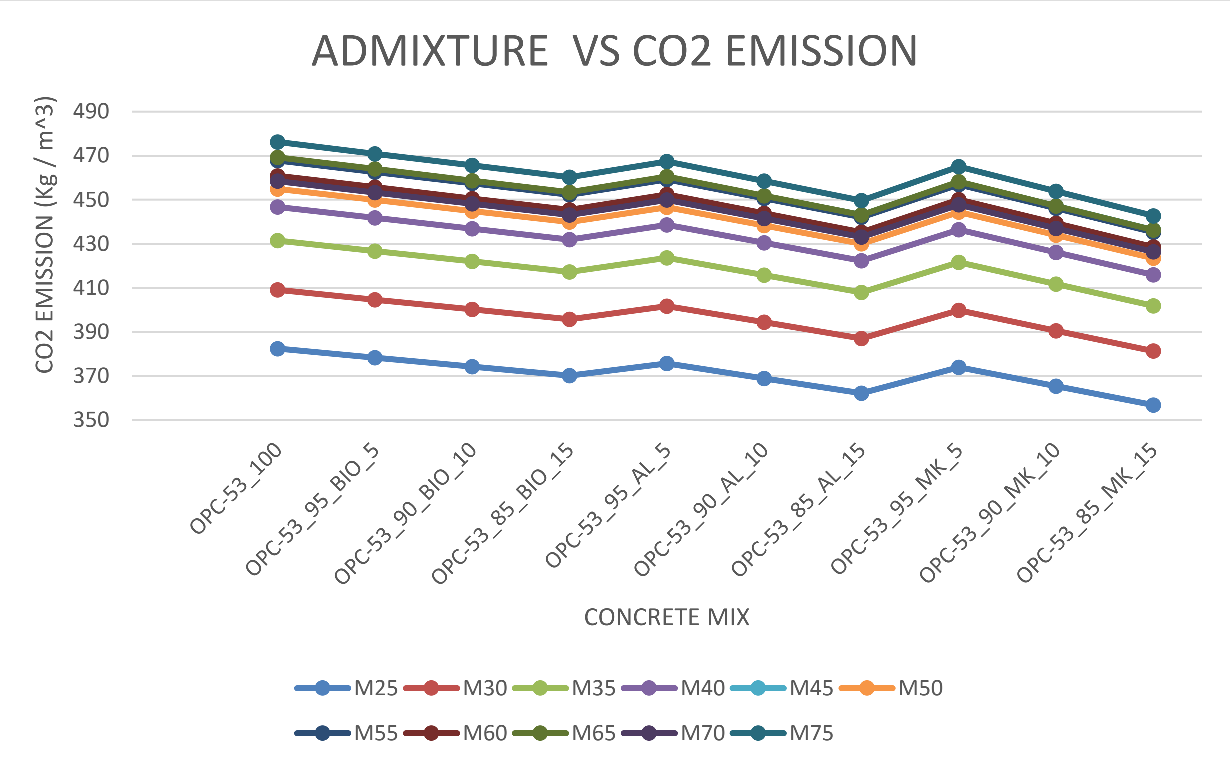
9.5 EMISSION ANALYSIS OF CONCRETE MIXES

The carbon dioxide emissions of concrete mixes were evaluated for different replacement levels of supplementary cementitious materials. The analysis indicates that CO_2 emissions increase with increasing binder content; however, partial replacement of cement with SCMs significantly reduces emissions due to lower clinker consumption.

Across all mixes, increasing the replacement level from 5% to 15% resulted in a consistent reduction in CO_2 emissions. Among the materials studied, Metakaolin (MK) and Alccofine (AL) demonstrated greater emission reduction compared to Biocement, primarily due to reduced clinker content and improved material efficiency.

Table 9.1: Average CO_2 Emission for M25 Concrete

Mix	CO_2 Emission (kg CO_2/m^3)
OPC	376.73
Bio 5%	372.93
Bio 10%	369.12
Bio 15%	365.31
AL 5%	370.24
AL 10%	363.75
AL 15%	357.26
MK 5%	368.47
MK 10%	360.20
MK 15%	351.93



The results indicate that the MK–15 mix achieved the lowest CO_2 emission value, representing a significant reduction compared to conventional OPC concrete. This finding highlights the effectiveness of supplementary cementitious materials in reducing the environmental footprint of concrete production while maintaining structural performance.

10. CONCLUSIONS

This study investigated the mechanical performance, durability characteristics, microstructural behavior, and environmental impact of concrete incorporating supplementary cementitious materials (SCMs) through experimental analysis and Life Cycle Assessment (LCA). Based on the results obtained, the following conclusions can be drawn:

- The incorporation of SCMs significantly reduced the carbon footprint of concrete. Increasing the replacement level from 5% to 15% resulted in a consistent decrease in CO_2 emissions, with the MK–15 mix achieving the lowest emission value of 351.93 kg CO_2/m^3, compared to 376.73 kg CO_2/m^3 for conventional OPC concrete.
- Among the SCMs studied, Alccofine and Metakaolin demonstrated greater emission reduction potential than Biocement due to reduced clinker content and improved material efficiency.
- The Alccofine-based concrete (AL–15) exhibited superior mechanical performance, achieving higher compressive strength (28.2 MPa) and improved split tensile strength compared to the Metakaolin-based mix.
- Flexural testing results indicated that the AL–15 beam demonstrated approximately 35–40% higher load-carrying capacity and improved stiffness compared to the MK–15 beam, confirming enhanced structural efficiency.
- Durability performance results showed lower water absorption for the Alccofine mix (0.565%) compared to the Metakaolin mix (0.637%), indicating reduced permeability and improved resistance to moisture ingress.
- Carbonation, acid attack, and sulphate resistance tests confirmed that both mixes exhibited satisfactory durability under aggressive environmental conditions, with Alccofine demonstrating improved resistance to carbonation and sulphate attack, while Metakaolin showed comparatively better resistance to acid exposure.
- Microstructural analysis using SEM and EDX revealed dense matrix formation, refined pore structure, and improved interfacial bonding in SCM-based concrete, supporting the observed improvements in strength and durability.
- Thermogravimetric analysis indicated that Metakaolin-based concrete exhibited superior thermal stability, whereas Alccofine-based concrete demonstrated enhanced mechanical strength and durability performance.

Overall, the results demonstrate that the use of supplementary cementitious materials, particularly Alccofine and Metakaolin at a 15% replacement level, provides an effective balance between structural performance, durability, and environmental sustainability. The adoption of these materials can significantly contribute to the development of low-carbon and high-performance concrete for modern construction applications.

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