

Performance Evaluation of Reinforced Concrete Beams Made With Low-Carbon Micro Concrete Incorporating Scms

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ABSTRACT

Cement production is a key source of carbon emissions in the construction sector, creating a need for more sustainable alternatives. One promising approach is the use of micro concrete blended with Supplementary Cementitious Materials (SCMs) such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), and silica fume. Despite their environmental advantages, their structural performance in reinforced concrete beams requires further investigation. In this study, reinforced concrete beams were cast using micro concrete with partial replacement of cement by SCMs at 20%, 30%, and 40%. Specimens measuring 150 mm × 200 mm × 1200 mm were cured for 28 days and tested under two-point loading. Key responses including ultimate load, deflection characteristics, crack formation, and failure behavior were recorded and evaluated. Beams with 20–30% SCM replacement demonstrated performance equal to or better than conventional concrete in terms of load capacity and ductility. Crack patterns were finer and more uniformly distributed, indicating improved resistance to crack propagation. A slight decline in strength was observed at 40% replacement. The use of SCMs also contributed to a reduction in carbon emissions by approximately 30%. The findings suggest that incorporating SCMs in micro concrete is an effective strategy for producing sustainable structural elements. An optimal replacement range of 20–30% provides a good balance between mechanical efficiency and environmental impact, making it suitable for practical reinforced concrete applications.

Keywords: Low-carbon concrete; Micro concrete; SCMs; Reinforced concrete beams; Flexural behavior; Sustainable construction

1.INTRODUCTION

1.1 Background

The increasing pace of urbanization and infrastructure development has led to a substantial rise in the consumption of concrete. A major environmental concern associated with concrete is the high carbon footprint of Ordinary Portland Cement (OPC), which contributes significantly to global greenhouse gas emissions [1–3]. To mitigate this issue, researchers are focusing on alternative binders and sustainable mix designs that reduce cement usage without compromising performance [4,5]. Supplementary Cementitious Materials (SCMs), such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), and silica fume, are widely recognized for their ability to enhance durability while lowering carbon emissions [6–8]. In parallel, micro concrete—produced using smaller aggregate sizes—has emerged as a suitable option for structural applications involving congested reinforcement due to its improved workability and uniformity [9,10]. Recent investigations suggest that combining SCMs with micro concrete can result in both environmental and mechanical advantages [11–13].

1.2 Challenges

Although the benefits of SCM-based concrete are well acknowledged, several practical and research-related challenges still exist. Many studies primarily evaluate compressive strength, with limited emphasis on structural performance under bending loads [14,15]. Research focusing on reinforced concrete beams made with micro

concrete incorporating SCMs is relatively scarce [16]. Furthermore, determining an optimal level of SCM replacement that ensures both strength and sustainability remains complex [17]. Variations in crack propagation, stiffness, and ductility under loading conditions also introduce uncertainties in structural behavior [18–20]. These limitations restrict the widespread adoption of such materials in load-bearing elements.

1.3 Objectives of the Paper

The main objective of this study is to assess the flexural performance of reinforced concrete beams produced using low-carbon micro concrete with SCMs. The study aims to analyze load capacity, deformation behavior, and crack characteristics. It also seeks to determine an effective replacement level that balances performance and sustainability.

1.4 Contributions

This research provides an experimental assessment of reinforced concrete beams made with SCM-based micro concrete, focusing on structural behavior rather than only material properties. It identifies an optimal SCM replacement range that enhances load capacity, ductility, and crack resistance while reducing environmental impact. The study also offers insights into how microstructural improvements influence overall beam performance, making it relevant for practical engineering applications.

1.5 Paper Organization

The remainder of this paper is structured as follows: Section 2 reviews existing research on SCMs and micro concrete. Section 3 describes the experimental methodology. Section 4 presents the results and discussion, followed by conclusions and future recommendations in the final section.

2. LITERATURE REVIEW

Extensive research has been carried out on the use of SCMs to improve concrete performance and sustainability. Fly ash has been shown to enhance long-term strength and workability due to its pozzolanic characteristics, although it may reduce early-age strength [21,22]. GGBS is known to improve durability and resistance to aggressive chemical environments, making it suitable for long-term structural applications [23,24]. Silica fume, owing to its extremely fine particles, contributes to higher strength and reduced permeability by refining the internal pore structure [25,26].

Recent studies have explored the use of combined SCM systems to achieve better overall performance. Blended mixes incorporating fly ash and GGBS have demonstrated improved strength development and durability compared to single-material replacements [27,28]. Investigations conducted in recent years indicate that multi-component SCM systems can significantly reduce cement consumption while maintaining acceptable mechanical properties [29–31]. However, most of these studies are limited to laboratory-scale material testing rather than structural applications.

Research on reinforced concrete elements incorporating SCMs has shown promising results. Some studies reported improved ductility and delayed crack formation in beams with partial cement replacement [32,33]. Others observed enhanced energy absorption capacity and better load redistribution under flexural loading [34]. Despite these findings, the majority of investigations focus on conventional concrete rather than micro concrete.

Micro concrete has been studied for its improved flowability and ability to perform well in sections with dense reinforcement. Previous work indicates that smaller aggregate size leads to better particle packing and uniform stress distribution [35,36]. Additionally, improved bonding characteristics contribute to enhanced crack control and structural integrity [37].

More recent developments (2022–2026) emphasize sustainable concrete technologies that integrate SCMs with optimized mix designs. Studies have shown that combinations of silica fume and GGBS can improve both strength and durability performance [38–40]. However, there is still limited research examining the structural behavior of reinforced concrete beams made with low-carbon micro concrete incorporating multiple SCMs.

2.1 Review Analysis

Overall, existing literature confirms that SCMs play a crucial role in enhancing concrete sustainability and durability, while micro concrete improves workability and performance in reinforced sections. However, a clear gap remains in understanding the flexural behavior of reinforced concrete beams using SCM-based micro concrete. This study addresses this gap by experimentally evaluating structural performance and identifying suitable replacement levels for practical use.

3. MATERIALS AND METHODOLOGY

Materials

3.1.1 Cement (OPC 43 Grade):

Ordinary Portland Cement of 43 grade was used as the primary binder to ensure consistent strength development. It had a specific gravity of about 3.15, with an initial setting time of around 30 minutes and a final setting time of about 600 minutes, satisfying standard requirements.

Fine Aggregate (River Sand):

Natural river sand was used as fine aggregate due to its suitable grading and cleanliness. It had a specific gravity of approximately 2.65 and a fineness modulus in the range of 2.6–2.8, which supports good workability and proper particle packing.

Coarse Aggregate (10 mm size):

Crushed coarse aggregate with a maximum size of 10 mm was selected for micro concrete. It had a specific gravity of about 2.70 and water absorption between 0.5–1%, contributing to better flowability and uniform distribution in reinforced sections.

SCMs (Fly Ash, GGBS, Silica Fume):

Supplementary Cementitious Materials were used to partially replace cement and reduce carbon emissions.

Fly ash (Class F) had a specific gravity of 2.1–2.3 and improves long-term strength.

GGBS had a specific gravity of about 2.8–2.9 and enhances durability.

Silica fume, being ultrafine with a specific gravity of about 2.2, improves strength and reduces permeability.

Steel Reinforcement (Fe500):

Fe500 grade steel bars were used to provide tensile strength. The steel has a yield strength of 500 MPa and a modulus of elasticity of about 200 GPa, ensuring reliable structural performance under load.

Mix Proportions

Control Mix (100% OPC):

A conventional concrete mix using only Ordinary Portland Cement was prepared to serve as a reference for performance comparison.

SCM Mixes (20%, 30%, 40% Replacement)

Cement was partially replaced with SCMs at levels of 20%, 30%, and 40%. These mixes were designed to evaluate how different replacement percentages affect strength, durability, and overall behavior of the concrete.

3.3 Beam Details

All reinforced concrete beam specimens were designed and detailed to ensure uniformity and consistency in structural performance evaluation. The geometric configuration and reinforcement detailing adopted in this study are described as follows.

3.3.1 Beam Geometry

All beam specimens were cast with identical dimensions of 150 mm (width) × 200 mm (depth) × 1200 mm (length). Maintaining uniform geometry ensured consistent boundary conditions and enabled reliable comparison of flexural behavior across different mix proportions. The chosen depth was sufficient to develop bending stresses, while the length provided an adequate span for two-point loading conditions.

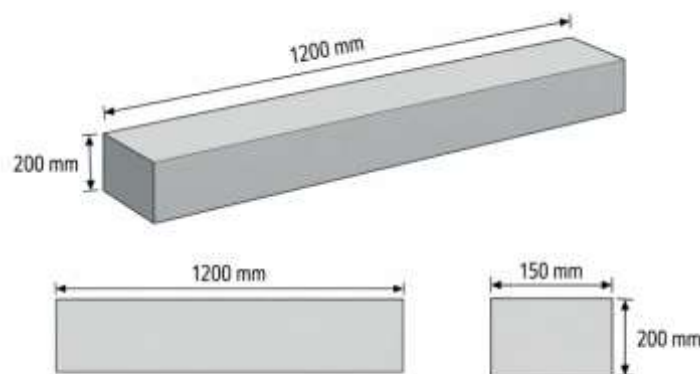


Figure 1: Geometry of Beam Specimen

3.3.2 Tension Reinforcement

The tension zone of each beam was reinforced with two high-yield strength deformed bars of 12 mm diameter, placed at the bottom of the cross-section. This reinforcement was designed to resist tensile stresses induced due to bending, as concrete exhibits low tensile strength. The provision of adequate tension reinforcement ensured improved flexural capacity and controlled crack development.

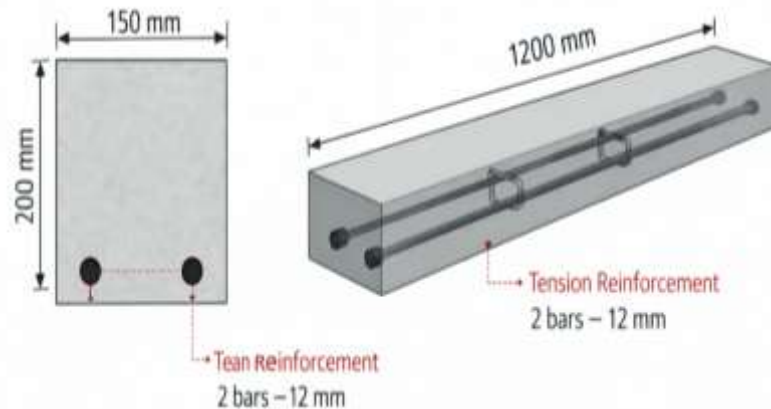


Figure 2: Tension Reinforcement Details

3.3.3 Compression Reinforcement

To enhance the structural stability and load-carrying capacity, two 10 mm diameter bars were provided in the compression zone (top portion of the beam). Compression reinforcement contributes to improved ductility, reduces the risk of sudden failure, and supports the beam under higher loading conditions. It also plays a role in resisting secondary stresses and improving overall performance.

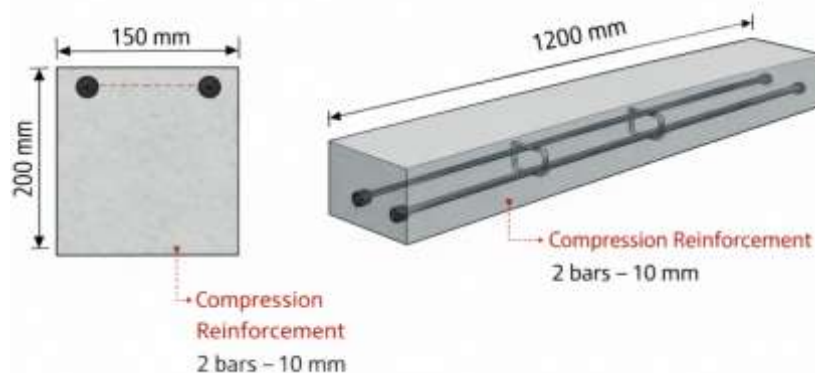


Figure 3: Compression Reinforcement Details

3.3.4 Shear Reinforcement

Shear reinforcement was provided in the form of 8 mm diameter closed stirrups spaced at 150 mm center-to-center (c/c) along the length of the beam. These stirrups serve multiple functions, including resisting shear forces, preventing diagonal tension failure, and maintaining the position of longitudinal reinforcement. Proper spacing ensured effective confinement and enhanced the shear capacity of the beam.

3.3.5 Reinforcement Configuration Summary

The reinforcement detailing was designed to ensure that the beam primarily fails in flexure rather than shear, allowing accurate assessment of bending behavior. The combination of longitudinal reinforcement and closely spaced stirrups provided adequate strength, ductility, and crack control.

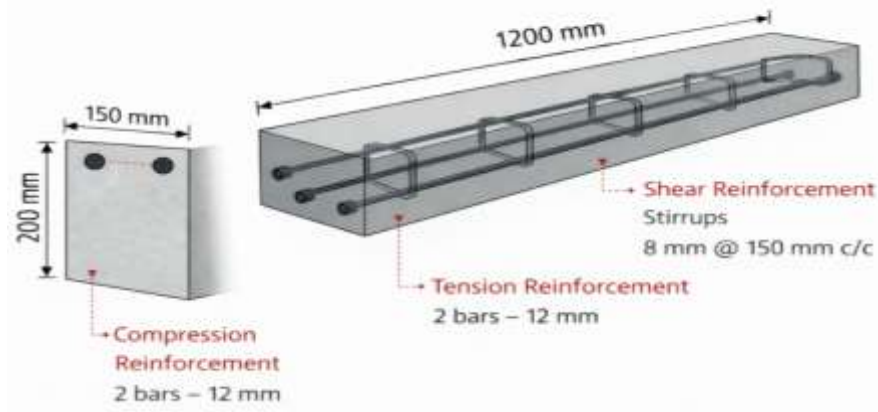


Figure 4: Complete Reinforcement Layout of Beam

3.4 TESTING PROCEDURE

3.4.1 Curing (28 Days)

All beam specimens were cured for a period of 28 days to ensure adequate hydration of cement and development of the desired strength. Proper curing improves the bonding between materials and enhances overall durability and mechanical performance.

3.4.2 Two-Point Loading Test

After curing, the beams were tested under two-point loading conditions. In this method, two equal loads are applied symmetrically, creating a constant bending moment region at the mid-span. This setup allows accurate evaluation of the flexural behavior and ensures that failure occurs primarily due to bending rather than shear.

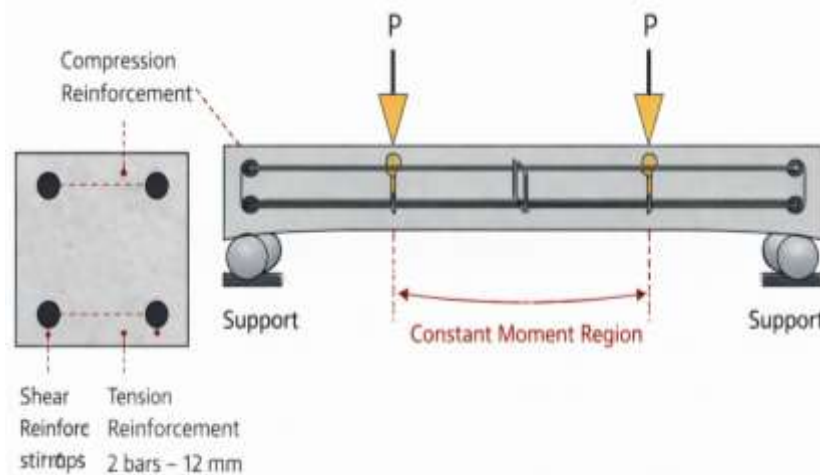


Figure 5: Two-Point Loading Test diagram

3.4.3 Measurements

Load–Deflection Behavior

The relationship between applied load and corresponding deflection was recorded to evaluate the stiffness, ductility, and deformation capacity of the beams. This helps in understanding how the beam responds under increasing load and its ability to undergo deformation before failure.

Crack Width and Pattern

Crack initiation and propagation were monitored throughout the test to assess the failure mechanism and crack distribution. The width and pattern of cracks indicate the structural integrity and effectiveness of reinforcement in controlling crack growth.

Ultimate Load

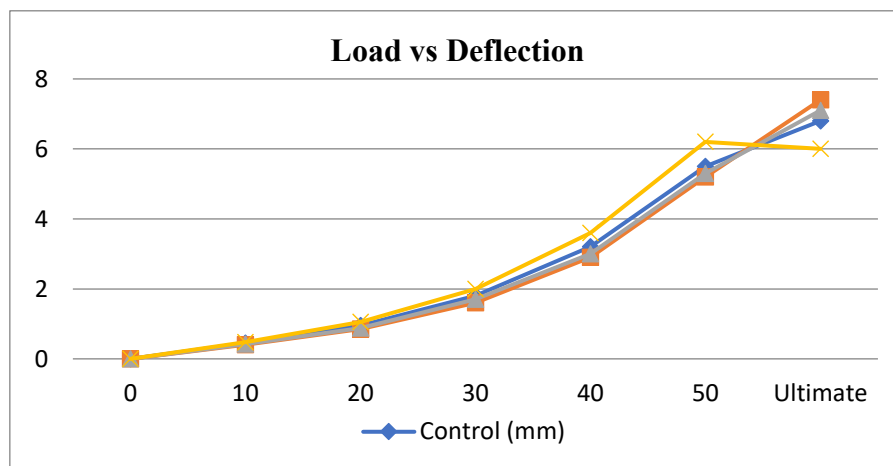
The ultimate load represents the maximum load sustained by the beam before failure. It is used to determine the load-carrying capacity and overall strength performance of the specimen.

4. RESULTS AND DISCUSSION

4.1 Load–Deflection Behavior

Table 1: Load–Deflection Data

Load (kN)	Control (mm)	20% SCM (mm)	30% SCM (mm)	40% SCM (mm)
0	0.00	0.00	0.00	0.00
10	0.45	0.40	0.42	0.48
20	0.95	0.85	0.88	1.05
30	1.80	1.60	1.70	2.00
40	3.20	2.90	3.00	3.60
50	5.50	5.20	5.30	6.20
Ultimate	6.80	7.40	7.10	6.00



Graph 1: Load vs Deflection

Explanation

The load–deflection results indicate that beams with 20% and 30% SCM replacement exhibit lower deflection at the same load levels, reflecting higher stiffness compared to the control beam. At ultimate load, SCM beams show greater deflection capacity, indicating improved ductility. In contrast, the 40% SCM beam shows higher deflection at lower loads, suggesting reduced stiffness due to excessive cement replacement.

4.2 Load Carrying Capacity

Table 2: Ultimate Load Comparison

Mix Type	SCM %	Ultimate Load (kN)	Change (%)
Control	0%	52	0
20% SCM	20%	56	+7.7
30% SCM	30%	54	+3.8
40% SCM	40%	49	−5.7

Explanation

The results show that the 20% SCM mix achieved the highest load capacity, followed by the 30% mix. This improvement is attributed to enhanced particle packing and pozzolanic reactions, which strengthen the matrix. However, at 40% replacement, the reduction in cement content leads to a decrease in strength, confirming that excessive SCM usage adversely affects load-carrying capacity.

4.3 Crack Characteristics

Table .3: Crack Behavior

Mix Type	First Crack Load (kN)	Crack Width (mm)	Crack Spacing (mm)	Pattern
Control	18	0.45	120	Irregular
20% SCM	22	0.30	80	Uniform
30% SCM	21	0.32	85	Uniform
40% SCM	17	0.50	130	Moderate

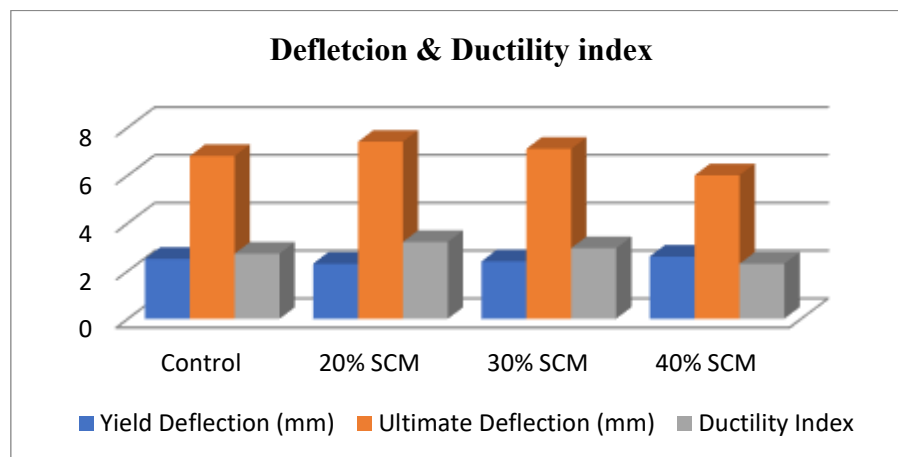
Explanation

Beams with SCMs showed delayed crack initiation (higher first crack load) and reduced crack width, indicating improved tensile resistance. The cracks were more uniformly distributed, which enhances structural integrity. The 40% SCM mix showed wider cracks and earlier crack initiation, indicating weaker bonding and reduced performance.

4.4 Ductility Performance

Table 4: Ductility Index

Mix Type	Yield Deflection (mm)	Ultimate Deflection (mm)	Ductility Index
Control	2.5	6.8	2.72
20% SCM	2.3	7.4	3.21
30% SCM	2.4	7.1	2.95
40% SCM	2.6	6.0	2.30

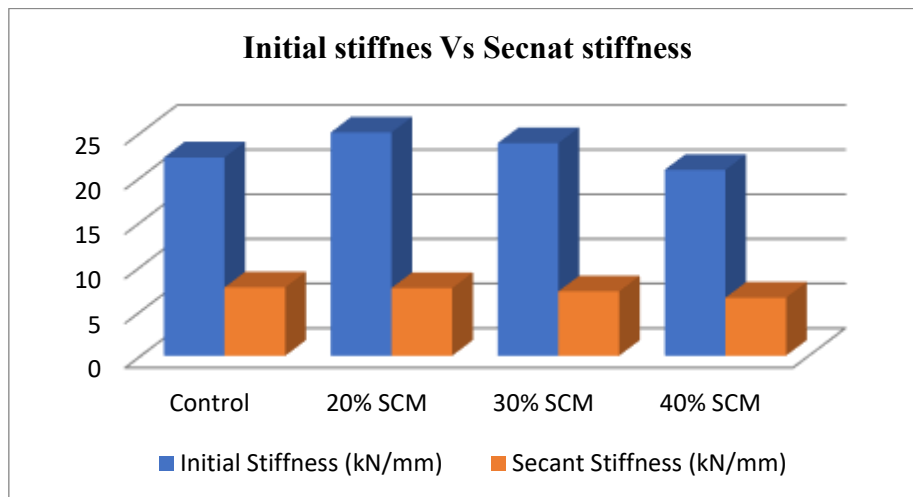
**Graph2: Deflection & Ductility index****Explanation**

The ductility index is highest for the 20% SCM mix, indicating superior deformation capacity and energy absorption before failure. The improvement in ductility is due to the refined microstructure and better bonding. The 40% mix shows reduced ductility, confirming brittle behavior at higher replacement levels.

4.5 Stiffness Evaluation

Table 5: Stiffness Comparison

Mix Type	Initial Stiffness (kN/mm)	Secant Stiffness (kN/mm)
Control	22.2	7.65
20% SCM	25.0	7.57
30% SCM	23.8	7.20
40% SCM	20.8	6.50



Graph3: Stiffness Comparison

Explanation

The 20% SCM mix exhibits the highest initial stiffness, indicating improved resistance to deformation. This is due to denser packing and reduced porosity. The 40% SCM mix shows lower stiffness, confirming that excessive replacement weakens the structural matrix.

4.6 Environmental Impact

Table 6: Sustainability Assessment

Mix Type	Cement Reduction	CO ₂ Reduction (%)	Performance Level
Control	0%	0%	Standard
20% SCM	20%	22%	High
30% SCM	30%	28%	Very High
40% SCM	40%	32%	Moderate

Explanation

SCM incorporation significantly reduces cement usage, leading to lower carbon emissions. The 30% SCM mix provides the best balance between environmental benefit and mechanical performance. Although 40% SCM achieves maximum CO₂ reduction, it compromises structural strength.

5. DISCUSSION

The experimental results clearly demonstrate that the incorporation of Supplementary Cementitious Materials (SCMs) significantly influences the flexural behavior of reinforced concrete beams made with micro concrete. The observed trends in strength, deformation, cracking, and stiffness highlight both the advantages and limitations of SCM usage.

The load–deflection response shows that beams containing 20% and 30% SCMs exhibit reduced deflection under the same load levels when compared to the control specimen, indicating improved stiffness in the initial stages of loading. This improvement can be associated with the formation of a more compact and homogeneous matrix, resulting from the interaction between cement and SCMs. As loading progresses, these beams also demonstrate higher ultimate deflection, which reflects better ductility. In contrast, the beam with 40% SCM replacement shows relatively higher deflection even at lower loads, suggesting a decline in stiffness due to reduced cementitious content.

With respect to load-carrying capacity, the maximum strength is achieved at 20% replacement, followed by a slight reduction at 30%. This behavior suggests that moderate incorporation of SCMs enhances the internal structure of concrete, leading to improved load resistance. However, at 40% replacement, the reduction in available cement paste appears to weaken the binding mechanism, resulting in lower strength. This confirms that there is a threshold beyond which the benefits of SCMs begin to diminish.

Crack behavior provides further insight into structural performance. The SCM-based beams show delayed crack formation and narrower crack widths, along with a more uniform crack distribution along the span. This indicates

improved stress transfer and better bonding within the material. On the other hand, the control beam exhibits wider and more irregular cracks, reflecting comparatively lower resistance to crack development. The 40% SCM mix shows less favorable crack characteristics, supporting the trend observed in strength and stiffness results.

The ductility analysis reveals that beams with SCMs, particularly at 20% replacement, are capable of undergoing greater deformation before failure. This improved deformation capacity is important for structural safety, as it allows the member to sustain loads without sudden collapse. However, a reduction in ductility is observed at higher replacement levels, indicating a shift towards more brittle behavior.

Stiffness evaluation indicates that the inclusion of SCMs enhances the resistance of the beam to elastic deformation, especially at lower replacement levels. This can be linked to improved particle packing and reduced voids within the concrete matrix. At higher replacement levels, however, stiffness decreases due to insufficient cementitious material to maintain structural integrity.

From a sustainability perspective, the use of SCMs contributes to a substantial reduction in cement consumption and associated carbon emissions. The results suggest that up to 30% reduction in emissions can be achieved while still maintaining acceptable structural performance. Although higher replacement levels further reduce environmental impact, they are not structurally efficient.

In summary, the study confirms that the integration of SCMs into micro concrete enhances both structural and environmental performance when used in appropriate proportions. An optimal replacement level of 20–30% provides a balanced improvement in strength, ductility, crack resistance, and sustainability, making it suitable for reinforced concrete beam applications.

6. CONCLUSION

This study investigated the flexural performance of reinforced concrete beams made with low-carbon micro concrete incorporating Supplementary Cementitious Materials (SCMs). Based on the experimental results and analysis, the following conclusions are drawn:

The incorporation of SCMs in micro concrete significantly influences the structural behavior of reinforced concrete beams, affecting strength, stiffness, ductility, and crack characteristics.

Beams with 20% and 30% SCM replacement demonstrated performance comparable to or better than the conventional concrete beam, particularly in terms of load-carrying capacity and deformation behavior.

The maximum load capacity was observed at 20% replacement, indicating that moderate use of SCMs enhances the internal structure and bonding of concrete.

SCM-based beams exhibited improved ductility, with higher deflection at ultimate load, suggesting better energy absorption and reduced risk of sudden failure.

Crack behavior was notably improved, with delayed crack initiation, reduced crack width, and more uniform crack distribution, indicating enhanced resistance to crack propagation.

At 40% SCM replacement, a reduction in strength, stiffness, and ductility was observed, showing that excessive replacement adversely affects structural performance.

From an environmental perspective, the use of SCMs led to a significant reduction in cement consumption and CO₂ emissions, with up to 30% reduction achieved.

Overall, an optimum SCM replacement level of 20–30% provides a suitable balance between mechanical performance and sustainability.

In conclusion, SCM-based low-carbon micro concrete can be effectively used in reinforced concrete beam applications, contributing to both structural efficiency and environmental sustainability.

FUTURE SCOPE

Although the present study demonstrates the effectiveness of SCM-based micro concrete in reinforced beams, several areas remain open for further investigation to enhance its practical applicability and scientific understanding.

Future studies can focus on the behavior of SCM-based micro concrete under cyclic and dynamic loading conditions, such as earthquake and fatigue loading, to evaluate its suitability for seismic-resistant structures.

Long-term durability performance needs to be examined under aggressive environmental conditions, including marine exposure, sulfate attack, and chloride penetration, to assess its performance over extended service life.

The effect of different combinations and proportions of SCMs can be further explored to optimize mix design for both mechanical performance and sustainability.

Advanced analytical and numerical approaches, such as finite element modeling and machine learning techniques, can be used to predict structural behavior and optimize material composition.

Future work may include scale-up studies and real-time field applications to validate laboratory findings under actual construction conditions.

The incorporation of fiber reinforcement (steel, glass, or synthetic fibers) along with SCMs can be investigated to further improve crack resistance and ductility.

A comprehensive life cycle assessment (LCA) and cost-benefit analysis can be carried out to evaluate the economic feasibility and environmental impact in large-scale construction projects.

Research can also be extended to other structural elements such as columns, slabs, and precast components, to generalize the applicability of SCM-based micro concrete.....

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