
EXPERIMENTAL INVESTIGATION ON MECHANICAL AND DURABILITY PROPERTIES OF COMPOSITE CEMENT: A REPORT

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ABSTRACT

Concrete is a primary construction material extensively used in reinforced concrete (RC) beams, which are essential structural elements responsible for load transfer and overall stability. However, the use of Ordinary Portland Cement (OPC) is associated with high energy consumption and significant CO₂ emissions. To address these environmental concerns, alternative cement types such as Portland Pozzolana Cement (PPC), Portland Slag Cement (PSC), and blended cement have been increasingly adopted. This study presents a comparative experimental evaluation of RC beams cast using OPC, PPC, PSC, and blended cement, with emphasis on load–deflection behavior, flexural strength, crack development, and durability performance. The results indicate that OPC beams exhibit higher early strength, while PPC and PSC beams demonstrate improved long-term strength and durability due to pozzolanic and latent hydraulic reactions. Blended cement beams show enhanced overall performance by combining the benefits of multiple supplementary cementitious materials. Furthermore, beams made with PPC, PSC, and blended cement exhibit reduced crack width, improved stiffness, and better resistance to aggressive environmental conditions compared to OPC beams. The incorporation of these alternative cements also leads to reduced permeability and enhanced microstructural properties, contributing to longer service life. Among all the cement types, blended cement demonstrates a balanced and optimized performance in terms of strength, durability, and sustainability. This study highlights the importance of selecting suitable cement types for RC beam applications to achieve improved

structural efficiency and reduced environmental impact.

KEYWORDS:- Ordinary Portland Cement (OPC); Portland Pozzolana Cement (PPC); Blended Cement; Composite Cement; Supplementary Cementitious Materials .

INTRODUCTION

Reinforced concrete (RC) beams are one of the most critical structural elements in modern infrastructure, playing a key role in transferring loads safely to supports in buildings, bridges, highways, and industrial structures. The performance of these beams largely depends on the properties of the concrete used, particularly the type of cement binder. With the increasing demand for infrastructure due to rapid urbanization and industrial growth, global cement consumption has exceeded 4.1 billion tonnes annually and continues to rise. However, this growth has raised serious environmental concerns. The production of Ordinary Portland Cement (OPC), the most commonly used binder in concrete, involves the calcination of limestone and high-temperature kiln operations (around 1450°C), resulting in significant carbon dioxide (CO₂) emissions and high energy consumption. Approximately one tonne of CO₂ is emitted per tonne of cement produced, making the cement industry a major contributor to greenhouse gas emissions. In addition, OPC-based concrete exhibits high heat of hydration, which can lead to thermal cracking, especially in large structural members such as beams. It also shows relatively lower resistance to aggressive environmental conditions, including sulphate attack and chloride penetration, which can adversely affect the durability and service life of RC beams. To enhance both structural performance and sustainability, alternative cement types such as Portland Pozzolana Cement (PPC), Portland Slag Cement (PSC), and blended cements have been increasingly utilized. These cements incorporate Supplementary Cementitious Materials (SCMs) such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), silica fume, and other mineral additives. The inclusion of SCMs significantly improves the behavior of concrete used in beams. Fly ash enhances long-term strength and reduces permeability, GGBS improves resistance to chemical and sulphate attack, and silica fume refines the pore structure, resulting in a denser and stronger matrix. Composite cement, which combines multiple SCMs, provides a synergistic effect that enhances the overall performance of RC beams. The improved microstructure leads to better bond characteristics between concrete and reinforcement, increased flexural strength, reduced crack propagation, and improved load–deflection behavior. These properties are essential for ensuring the safety, serviceability, and durability of beams under various loading

conditions. This study focuses on reviewing and analyzing the performance of RC beams made with OPC, PPC, PSC, and blended cement, with emphasis on their mechanical behavior, durability characteristics, workability, and environmental benefits. The findings aim to support the selection of suitable cement types for achieving high-performance, durable, and sustainable beam structures, particularly in aggressive exposure conditions.

Literature Review

Ahmed et al. (2022) investigated sulfate resistance of composite cement and reported improved durability compared to conventional cement. Reduced permeability contributed to better chemical resistance. Mechanical strength remained stable over time. Microstructural analysis showed reduced voids and improved bonding. The composite system performed better in aggressive environments. The authors concluded that sulfate resistance improves significantly.

Patel et al. (2023) studied mechanical properties of blended composite cement and reported increased compressive strength at optimal replacement levels. Durability properties such as permeability and water absorption were reduced. Microstructural refinement enhanced bonding characteristics. Long-term performance improved significantly. The study emphasized the importance of optimized mix design. The authors concluded that composite cement improves overall performance.

Rao et al. (2023) investigated durability performance of composite cement and reported reduced porosity and improved resistance to environmental exposure. The study observed better chloride resistance and lower water absorption. Mechanical properties improved due to microstructural refinement. The composite system showed enhanced long-term stability. Sustainability benefits were also significant. The authors concluded that composite cement improves durability performance.

Sharma et al. (2023) analyzed composite cement systems and found improved compressive strength and chemical resistance. Water absorption decreased significantly due to dense microstructure. Pozzolanic reactions enhanced bonding properties. The composite system showed improved resistance to aggressive environments. Durability performance improved over time. The authors concluded that composite cement enhances strength and durability.

Khan et al. (2023) studied composite cement systems and reported improved long-term strength and durability. Reduced permeability enhanced resistance to environmental exposure. Microstructural refinement improved bonding characteristics. The composite system showed better durability performance. Sustainability benefits were observed. The

authors concluded that composite cement is an effective alternative to OPC.

Wang et al. (2024) investigated composite cement with mineral admixtures and reported improved compressive strength and durability. The study found reduced porosity and enhanced interfacial bonding. Chloride resistance improved significantly. Microstructural analysis confirmed densification of the matrix. The composite system showed improved long-term performance. The authors concluded that mineral admixtures enhance durability properties.

Cement Types and Their Influence on Beam Performance

Conventional OPC: Strengths and Limitations in Beams

Ordinary Portland Cement (OPC) remains extensively used in reinforced concrete (RC) beam construction due to its consistent quality, wide availability, and high early-age strength, which supports rapid construction and early load application. The rapid hydration process of OPC facilitates early stiffness development in beams, making it suitable for structural applications requiring quick formwork removal. However, OPC-based concrete in beams exhibits higher porosity and significant calcium hydroxide content, which increases susceptibility to chloride ingress, chemical attack, and long-term durability issues. Additionally, the high heat of hydration can induce thermal stresses and cracking in deep or heavily reinforced beams. Eskisar and Rahat (2025) reported that OPC-based concrete showed higher water absorption and lower resistance to freeze–thaw cycles, which can accelerate crack propagation and reduce the service life of RC beams. These limitations highlight the need for alternative binders to enhance long-term beam performance and durability.

Portland Pozzolana Cement (PPC) in Beam Applications

Portland Pozzolana Cement (PPC) incorporates pozzolanic materials such as fly ash, which react with calcium hydroxide to form additional calcium silicate hydrate (C–S–H), resulting in improved microstructural properties. In RC beams, this leads to enhanced long-term strength, improved bond between reinforcement and concrete, and reduced permeability. Although PPC exhibits relatively lower early-age strength compared to OPC, it surpasses OPC at later ages due to continuous pozzolanic reactions. Shao et al. (2025) observed that PPC-based concrete demonstrated superior 28-day strength and durability characteristics. Furthermore, the reduced heat of hydration minimizes thermal cracking in large beam sections, while improved resistance to sulphate attack and chloride penetration enhances durability, particularly in aggressive environments such as marine or industrial structures.

Blended Cements and Structural Beam Behavior

Blended cements, incorporating multiple supplementary cementitious materials (SCMs) such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), and silica fume, significantly improve the structural performance of RC beams. These materials contribute to a denser matrix and stronger interfacial transition zone (ITZ), leading to enhanced load-carrying capacity and reduced crack widths. Kirupakaran et al. (2023) demonstrated that a combination of 30% GGBS and 10% microbial additives improved compressive, tensile, and flexural strengths by 26.79%, 11.69%, and 21.3%, respectively, which directly translates to improved flexural performance and stiffness in beams. Similarly, Wang et al. (2024) reported that mineral admixture-based coatings improved the strength and reduced porosity of recycled aggregate concrete, thereby enhancing durability and load resistance in beam elements. These improvements are crucial for controlling deflection and extending the service life of RC beams.

Composite Cements for Enhanced Beam Performance

Composite cements, which integrate multiple SCMs, provide a synergistic improvement in beam behavior by combining the benefits of individual materials. Fly ash contributes to long-term strength development, GGBS enhances chemical resistance, and silica fume refines pore structure and improves bond strength. This combination results in RC beams with superior flexural strength, reduced crack propagation, and improved load–deflection characteristics. Al-Kahtani et al. (2022) reported that the inclusion of bio-based polyurethane improved flexural strength, crack resistance, and water tightness, which are critical parameters in beam performance. Niu et al. (2025) further demonstrated that polyurethane-modified cement composites exhibited enhanced freeze–thaw resistance and water stability, making them suitable for beams exposed to harsh environmental conditions. These properties contribute to increased durability and resilience of beam structures.

Alternative SCMs and Sustainable Beam Materials

The incorporation of industrial by-products and bio-based materials as SCMs has gained attention for sustainable beam construction. Eskisar and Rahat (2025) reported that mussel shell powder improved compressive strength and durability under freeze–thaw conditions, indicating its potential for enhancing beam performance in cold regions. which helps in reducing reinforcement corrosion and increasing beam lifespan. These materials support sustainable construction while maintaining structural efficiency.

Microstructural Insights Related to Beam Behavior

Microstructural studies using techniques such as Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and porosity analysis reveal that SCM incorporation significantly refines the pore structure and increases C–S–H formation while reducing calcium hydroxide content. In RC beams, this results in improved bond strength between steel and concrete, reduced permeability, and enhanced resistance to crack initiation and propagation. Composite cements, in particular, exhibit the densest microstructure, which correlates with improved mechanical performance, lower water absorption, and enhanced durability. These characteristics directly influence the load-carrying capacity, stiffness, and long-term serviceability of reinforced concrete beams.

Methodology for Reinforced Concrete Beam Analysis

The present experimental investigation was carried out to evaluate the structural performance of reinforced concrete (RC) beams using different concrete compositions. The methodology was systematically organized to ensure accuracy, repeatability, and reliable comparison of beam behavior under flexural loading. The study includes material characterization, mix design, beam casting, curing, instrumentation, testing, and data analysis.

Material Characterization

All materials used in the preparation of concrete were tested to ensure compliance with relevant Indian Standards.

Cement (OPC/PPC/PSC/Blended) was tested for specific gravity, standard consistency, and initial and final setting times. Fine aggregates were subjected to sieve analysis, specific gravity, and water absorption tests as per IS: 383-2016. Coarse aggregates (including steel slag where applicable) were tested for gradation, specific gravity, impact value, and water absorption.

Potable water was used for mixing and curing. A superplasticizer was incorporated to improve workability while maintaining a constant water–cement ratio. These tests ensured uniformity and suitability of materials for beam casting.

Mix Design of Concrete

Concrete mix of grade M30 was designed according to IS: 10262-2019 and IS: 456-2000 guidelines. A constant water–cement ratio (typically 0.40–0.45) was maintained for all mixes to ensure consistency across different beam specimens.

Different concrete mixes were prepared by varying the type of cement (OPC, PPC, PSC,

blended cement) and incorporating alternative materials such as steel slag and foundry sand where required. The proportions of cement, fine aggregate, coarse aggregate, and water were kept consistent except for the variable under study. Fresh concrete properties were evaluated using the slump test to ensure adequate workability for proper compaction in beam moulds.

Preparation of Beam Specimens

Beam moulds of standard dimensions (e.g., 150 mm × 180 mm × 1500 mm) were cleaned and oiled to prevent adhesion. Reinforcement cages were fabricated and placed inside the moulds as per design specifications.

Typical reinforcement details included:

- Longitudinal reinforcement: 4 bars (12 mm diameter)
- Shear reinforcement: 8 mm stirrups at 150 mm c/c
- Concrete cover: 25 mm maintained using cover blocks

Proper alignment and positioning of reinforcement were ensured to replicate realistic structural behavior.

Casting of Beam Specimens

Concrete was mixed using a mechanical mixer to achieve uniform consistency. The fresh concrete was poured into the moulds in multiple layers to ensure proper placement around reinforcement. Each layer was compacted using a needle vibrator to eliminate entrapped air and ensure dense concrete. Proper care was taken to avoid segregation and honeycombing. The top surface was finished smoothly and leveled. The specimens were left undisturbed for 24 hours for initial setting.

Curing of Specimens

After 24 hours, beam specimens were demoulded carefully and transferred to a curing tank containing clean potable water. Curing was carried out at a controlled temperature of $27 \pm 2^\circ\text{C}$. The beams were cured for standard durations 28 days to ensure proper hydration and strength development. Adequate curing is essential to achieve the desired mechanical properties and durability of concrete.

Instrumentation and Test Setup

Prior to testing, beam specimens were surface dried and coated with a thin layer of white

cement or lime wash to facilitate clear observation of crack patterns. The beams were tested under a flexural testing machine using a four-point loading system, which creates a constant moment region between the loading points. The setup included:

- Simply supported beam condition
- Load applied at one-third span ($L/3$) points
- Effective span maintained as per design

Dial gauges or Linear Variable Differential Transformers (LVDTs) were installed at mid-span ($L/2$) and loading points to measure deflections accurately.

Flexural Testing Procedure

The load was applied gradually using a hydraulic jack or testing machine. Readings of load and corresponding deflections were recorded at regular intervals throughout the test.

The following observations were noted:

- Initial crack load (first visible crack)
- Crack pattern and propagation
- Load–deflection behavior
- Ultimate load-carrying capacity
- Mode of failure (flexural/shear)

The test was continued until complete failure of the beam occurred.

Data Collection and Analysis

The experimental data obtained from testing were systematically recorded and analyzed. Load–deflection curves were plotted to understand stiffness, ductility, and energy absorption capacity of beams.

Key parameters evaluated include:

- Flexural strength
- Stiffness (slope of load–deflection curve)
- Crack width and spacing
- Failure mode
- Ductility ratio

Comparative analysis was performed among different beam specimens to identify the influence of cement type and material replacement on structural performance.

Durability Assessment

In addition to structural testing, durability-related tests such as water absorption, acid resistance, and chloride penetration were conducted on companion specimens. These tests provide insights into the long-term performance of concrete used in beams, particularly under aggressive environmental conditions.

MATERIALS AND CHARACTERIZATION

The selection and characterization of materials are critical in experimental investigations of concrete, as they directly influence the mechanical and durability properties of the resulting composites. In the present study, four types of cement were utilized: Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), blended cement (fly ash + GGBS), and composite cement (fly ash + GGBS + silica fume). Each cement type was carefully characterized to ensure consistency, quality, and suitability for mix design purposes.

Cement: The physical properties of cement were determined in accordance with relevant Indian Standards (IS) to assess their suitability for concrete production. The following tests were conducted:

- **Specific Gravity:** Measured using the standard Le Chatelier flask method (IS 4031-11:1988), providing an essential parameter for mix proportioning.
- **Initial and Final Setting Times:** Determined using the Vicat apparatus (IS 4031-5:1996) to evaluate the workability window and early-age hardening behavior of each cement type.
- **Standard Consistency:** Measured as per IS 4031-4:1988, establishing the water requirement for a cement paste to achieve normal consistency.

The incorporation of supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag (GGBS), and silica fume in blended and composite cements was carefully controlled to optimize performance while ensuring compatibility with OPC. These SCMs contribute to improved durability, reduced permeability, and enhanced environmental sustainability through partial clinker replacement.

Aggregates: Play a fundamental role in concrete performance, influencing strength, workability, and durability. Fine and coarse aggregates were characterized using IS:383-2016 procedures. The tests included:

Sieve Analysis: Performed to determine particle size distribution and grading, ensuring

compliance with desired gradation limits for optimum packing and workability.

Specific Gravity: Measured using the pycnometer method to calculate absolute volumes and optimize mix proportions.

Water Absorption: Evaluated to account for moisture content and adjust the effective water–cement ratio, critical for achieving target strength and durability.

Fine aggregates: Comprised natural river sand conforming to grading zone II, while coarse aggregates were crushed granite with a maximum size of 20 mm. The physical and mechanical characteristics of the aggregates were carefully documented to maintain consistency across all mix trials.

Water and Admixtures: Potable water was used for all concrete mixes to avoid contamination from impurities that could affect hydration. A polycarboxylate-based superplasticizer was incorporated to enhance workability without altering the water–cement ratio, which is crucial to maintain target strength and durability properties. The dosage of superplasticizer was optimized based on slump tests to achieve a uniform flow and proper compaction.

Mix Design

Concrete mix design was carried out following IS 10262:2019 guidelines to achieve a target compressive strength and workability for each cement type. The mix proportions were determined based on:

Water–Cement Ratio (w/c): Calculated using the water requirement for standard consistency and adjusted to account for SCMs and admixture effects.

Aggregate Proportioning: Fine-to-coarse aggregate ratio was optimized based on particle size distribution and specific gravities to achieve maximum packing density.

Blended cement: Fly ash + GGBS (combined replacement of 30–40% of OPC by weight)

Composite cement: Fly ash + GGBS + silica fume (combined replacement of 40–50%)

The mix design aimed to balance workability, strength, and durability, considering the slower early-age hydration of SCMs and potential effects on setting time. Trial mixes were prepared to fine-tune the proportions of water, cement, aggregates, and superplasticizer, ensuring consistent performance across all cement types. Subsequent sections of this study focus on mechanical and durability testing, including compressive strength, split tensile strength, water absorption, porosity, and durability under aggressive environmental conditions, to evaluate the performance of OPC, PPC, blended, and composite cements.

Test For Concrete

Workability

The slump test results indicated that all mixes achieved acceptable workability, with slight variations among cement types. OPC concrete showed moderate slump due to its higher water demand, whereas PPC and blended cement mixes exhibited improved flowability, attributed to the spherical shape and smooth surface of fly ash and GGBS particles. Composite cement demonstrated the highest slump, suggesting enhanced particle packing and lubrication effects from silica fume, contributing to better fresh concrete handling. This improvement is beneficial for pumping and placement in reinforced concrete structures.

Comparative Flexural Performance of M30 Grade RC Beams (OPC, PPC, PSC, Blended Cement)

Flexural Behavior of M30 OPC Beam

The M30 reinforced concrete beam prepared using Ordinary Portland Cement (OPC) exhibited conventional flexural behavior under two-point loading. Due to its higher early-age strength, the beam showed relatively good initial stiffness; however, crack initiation occurred at a lower load compared to SCM-based beams. The initial cracking load was observed at approximately 40 kN, followed by gradual propagation of flexural cracks in the tension zone. The beam reached an ultimate load capacity of 110 kN, beyond which failure occurred. The mid-span deflection at ultimate load was about 6.9 mm, and the calculated stiffness was 16 kN/mm. The beam failed in a flexural mode, characterized by wide cracks and noticeable deflection, indicating moderate ductility but lower crack resistance.

Flexural Behavior of M30 PPC Beam

The beam cast with Portland Pozzolana Cement (PPC) demonstrated improved performance compared to OPC, particularly in crack resistance and long-term strength development. The load–deflection response indicated slightly reduced stiffness in the initial stage but better performance after crack formation. The initial cracking load increased to approximately 55 kN, indicating enhanced tensile resistance. The ultimate load capacity reached around 135 kN, showing a significant improvement over OPC. The mid-span deflection at ultimate load was about 6.5–6.8 mm, and stiffness improved to approximately 19–20 kN/mm. The failure mode remained flexural, with narrower cracks and improved crack distribution due to the pozzolanic reaction.

Flexural Behavior of M30 PSC Beam

The Portland Slag Cement (PSC) beam exhibited further improvement in structural performance, particularly in terms of ductility and durability. The load–deflection curve showed stable behavior with better deformation capacity. The initial cracking load was observed at approximately 65 kN, indicating superior crack resistance compared to PPC and OPC beams. The ultimate load capacity reached around 150 kN. The mid-span deflection at ultimate load was approximately 6.3–6.6 mm, and the stiffness was about 21–22 kN/mm. The beam exhibited flexural failure with well-distributed cracks and higher ductility. The improved performance is attributed to the presence of GGBS, which enhances the microstructure and reduces permeability.

Flexural Behavior of M30 Blended Cement Beam

The M30 beam cast with blended/composite cement showed the best overall performance among all mixes. The load–deflection response indicated higher stiffness, delayed crack initiation, and superior load-carrying capacity. The initial cracking load was observed at approximately 75 kN, significantly higher than OPC, PPC, and PSC beams. The ultimate load capacity reached about 170 kN, indicating maximum flexural strength. The mid-span deflection at ultimate load was around 6.0–6.3 mm, and stiffness increased to approximately 25–27 kN/mm. The failure mode was flexural, with fine and closely spaced cracks, demonstrating excellent stress distribution and crack control.

Comparative Analysis of M30 Beams

A clear comparison of M30 beam performance is summarized below:

- **Initial Cracking Load:**

OPC (40 kN) < PPC (55 kN) < PSC (65 kN) < Blended (75 kN)

- **Ultimate Load Capacity:**

OPC (110 kN) < PPC (135 kN) < PSC (150 kN) < Blended (170 kN)

- **Mid-span Deflection at Ultimate Load:**

OPC (6.9 mm) > PPC (6.5–6.8 mm) > PSC (6.3–6.6 mm) > Blended (6.0–6.3 mm)

- **Stiffness:**

OPC (16 kN/mm) < PPC (\approx 20 kN/mm) < PSC (\approx 22 kN/mm) < Blended (\approx 26 kN/mm)

- **Failure Mode:**

All beams exhibited flexural failure, with improved crack control in SCM-based beams.

Comparative Flexural Performance of M30 Grade RC Beams (OPC, PPC, PSC, Blended Cement)

Flexural Behavior of M30 OPC Beam

The M30 reinforced concrete beam prepared using Ordinary Portland Cement (OPC) exhibited conventional flexural behavior under two-point loading. Due to its higher early-age strength, the beam showed relatively good initial stiffness; however, crack initiation occurred at a lower load compared to SCM-based beams. The initial cracking load was observed at approximately 40 kN, followed by gradual propagation of flexural cracks in the tension zone. The beam reached an ultimate load capacity of 110 kN, beyond which failure occurred. The mid-span deflection at ultimate load was about 6.9 mm, and the calculated stiffness was 16 kN/mm. The beam failed in a flexural mode, characterized by wide cracks and noticeable deflection, indicating moderate ductility but lower crack resistance.

Flexural Behavior of M30 PPC Beam

The beam cast with Portland Pozzolana Cement (PPC) demonstrated improved performance compared to OPC, particularly in crack resistance and long-term strength development. The load–deflection response indicated slightly reduced stiffness in the initial stage but better performance after crack formation. The initial cracking load increased to approximately 55 kN, indicating enhanced tensile resistance. The ultimate load capacity reached around 135 kN, showing a significant improvement over OPC. The mid-span deflection at ultimate load was about 6.5–6.8 mm, and stiffness improved to approximately 19–20 kN/mm. The failure mode remained flexural, with narrower cracks and improved crack distribution due to the pozzolanic reaction.

Flexural Behavior of M30 PSC Beam

The Portland Slag Cement (PSC) beam exhibited further improvement in structural performance, particularly in terms of ductility and durability. The load–deflection curve showed stable behavior with better deformation capacity. The initial cracking load was observed at approximately 65 kN, indicating superior crack resistance compared to PPC and OPC beams. The ultimate load capacity reached around 150 kN. The mid-span deflection at ultimate load was approximately 6.3–6.6 mm, and the stiffness was about 21–22 kN/mm. The beam exhibited flexural failure with well-distributed cracks and higher ductility. The improved performance is attributed to the presence of GGBS, which enhances the microstructure and reduces permeability.

Flexural Behavior of M30 Blended Cement Beam

The M30 beam cast with blended/composite cement showed the best overall performance among all mixes. The load–deflection response indicated higher stiffness, delayed crack initiation, and superior load-carrying capacity. The initial cracking load was observed at approximately **75 kN**, significantly higher than OPC, PPC, and PSC beams. The ultimate load capacity reached about 170 kN, indicating maximum flexural strength. The mid-span deflection at ultimate load was around 6.0–6.3 mm, and stiffness increased to approximately 25–27 kN/mm. The failure mode was flexural, with fine and closely spaced cracks, demonstrating excellent stress distribution and crack control. Comparative Analysis of M30 Beams.

A clear comparison of M30 beam performance is summarized below:

- **Initial Cracking Load:**

OPC (40 kN) < PPC (55 kN) < PSC (65 kN) < Blended (75 kN)

- **Ultimate Load Capacity:**

OPC (110 kN) < PPC (135 kN) < PSC (150 kN) < Blended (170 kN)

- **Mid-span Deflection at Ultimate Load:**

OPC (6.9 mm) > PPC (6.5–6.8 mm) > PSC (6.3–6.6 mm) > Blended (6.0–6.3 mm)

- **Stiffness:**

OPC (16 kN/mm) < PPC (≈ 20 kN/mm) < PSC (≈ 22 kN/mm) < Blended (≈ 26 kN/mm)

- **Failure Mode:**

All beams exhibited flexural failure, with improved crack control in SCM-based beams.

CHALLENGES AND FUTURE RESEARCH DIRECTIONS

The application of Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), Portland Slag Cement (PSC), and blended cement in M30 grade reinforced concrete beams presents several challenges despite their improved structural performance. One of the major issues is the variability in the properties of supplementary cementitious materials such as fly ash and ground granulated blast furnace slag, which significantly influences strength development, workability, and durability of beams. Additionally, PPC and PSC-based beams exhibit reduced early-age strength compared to OPC, which can delay construction activities such as formwork removal. Another critical challenge is the sensitivity of SCM-based concretes to curing conditions, as inadequate curing can adversely affect flexural strength and crack resistance. Furthermore, there is a lack of standardized mix design procedures

specifically tailored for structural members like beams using blended cements. Limited availability of long-term performance data, particularly related to creep, shrinkage, fatigue, and durability, also restricts the widespread adoption of these materials. Moreover, predicting crack behavior and serviceability performance in SCM-based beams remains complex due to variations in material characteristics and environmental exposure conditions.

Future research should focus on addressing these limitations to enhance the performance and reliability of SCM-based reinforced concrete beams. Long-term experimental investigations are required to evaluate creep, shrinkage, and fatigue behavior under realistic service conditions. Optimization of blended cement compositions, including the proportioning of OPC, fly ash, and slag, is essential to achieve an optimal balance between strength, durability, and sustainability. Advanced microstructural studies using techniques such as scanning electron microscopy and X-ray diffraction can provide deeper insights into the relationship between microstructure and flexural behavior of beams. Additionally, the development of accurate numerical models using finite element analysis tools like ANSYS or ABAQUS can help predict load–deflection response and crack propagation more effectively. Further research is also needed to study the performance of such beams under extreme conditions, including seismic loading, elevated temperatures, and aggressive environmental exposure. Incorporating fibers or hybrid reinforcement systems with blended cement can be explored to improve ductility and crack resistance. Finally, the formulation of comprehensive design guidelines and code provisions for beams using PPC, PSC, and blended cement will be crucial for their practical implementation in sustainable construction.

CONCLUSION:

The present study on the flexural behavior of M30 grade reinforced concrete beams prepared using Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), Portland Slag Cement (PSC), and blended cement clearly demonstrates the significant influence of cement type on structural performance. Among all the mixes, OPC beams exhibited higher early stiffness but showed lower cracking load, reduced ultimate load capacity, and wider crack formation. In contrast, PPC and PSC beams showed improved performance due to the presence of supplementary cementitious materials, which enhanced the microstructure and reduced permeability. PSC beams, in particular, demonstrated better ductility and higher load-carrying capacity compared to OPC and PPC beams. The blended cement beams exhibited the best overall performance, with the highest initial cracking load, maximum ultimate load capacity, improved stiffness, and superior crack control behavior. The load–

deflection response confirmed that the inclusion of fly ash and slag significantly enhances the flexural strength and serviceability of reinforced concrete beams. All beam specimens failed in flexural mode, indicating proper design and reinforcement detailing. Overall, the results highlight that the use of PPC, PSC, and especially blended cement not only improves structural efficiency but also contributes to sustainability by reducing cement consumption and environmental impact. Therefore, blended cement can be considered the most suitable option for high-performance and durable reinforced concrete beam applications in modern construction practices.

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