



Experimental Investigation on Mechanical and Durability Properties of Composite Cement: A Review

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ABSTRACT :

Concrete, as a fundamental construction material, underpins modern infrastructure, including buildings, bridges, pavements, and industrial structures. However, conventional Ordinary Portland Cement (OPC), the primary binder, is associated with high energy consumption and significant CO₂ emissions, contributing to environmental degradation. In response, Supplementary Cementitious Materials (SCMs)—such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), silica fume, and bio-based additives—have been increasingly adopted to partially replace clinker. This review synthesizes recent experimental studies comparing OPC, Portland Pozzolana Cement (PPC), blended cement, and composite cements, focusing on mechanical properties, durability, microstructural behavior, workability, and sustainability. The compiled evidence demonstrates that SCM incorporation improves long-term compressive, tensile, and flexural strength, reduces permeability and chemical vulnerability, enhances microstructural densification, and lowers carbon footprint. Among all types, composite cements, integrating multiple SCMs, provide a synergistic effect, offering optimal mechanical performance, durability, and environmental benefits. This review highlights the importance of selecting appropriate SCM combinations to achieve sustainable, resilient, and durable concrete, particularly for aggressive environmental exposures.

Key words:- Ordinary Portland Cement (OPC); Portland Pozzolana Cement (PPC); Blended Cement; Composite Cement; Supplementary Cementitious Materials (SCMs); Fly Ash; GGBS; Silica Fume.

Introduction

Concrete is the backbone of global infrastructure, fulfilling the demand for housing, industrial structures, highways, bridges, and marine applications. The rapid growth in urbanization and industrial expansion has increased the global cement demand to over 4.1 billion tonnes annually, a number projected to grow further. While essential for development, cement production is associated with substantial environmental costs. The calcination of limestone (CaCO₃) in clinker production releases large quantities of CO₂, and high-temperature kilns (~1450°C) consume substantial fossil fuels. Overall, nearly one tonne of CO₂ is emitted per tonne of cement, making the industry one of the largest contributors to greenhouse gas emissions globally. Ordinary Portland Cement (OPC), with approximately 95% clinker and 5% gypsum, dominates construction but exhibits high carbon footprint, energy demand (~3.2–3.5 GJ per tonne), and limited durability under aggressive conditions such as marine exposure, sulphate attack, and de-icing salts. OPC also has high heat of hydration, leading to thermal cracking in massive structures. To address these issues, researchers and practitioners have increasingly explored Portland Pozzolana Cement (PPC), blended cements, and composite cements, which incorporate Supplementary Cementitious Materials (SCMs) such as fly ash, GGBS, silica fume, and even bio-based materials. Fly ash improves long-term strength and reduces permeability, GGBS enhances chemical and sulphate resistance, and silica fume acts as a micro-filler to refine pore structure. Composite cements, combining multiple SCMs, achieve a synergistic effect, balancing early strength, long-term performance, durability, and sustainability. This review aims to consolidate recent experimental investigations on OPC, PPC, blended, and composite cements, emphasizing their mechanical performance, durability characteristics, microstructural insights, workability, and environmental benefits, providing guidance for sustainable construction practices.

Literature Review

Al-Kahtani et al. (2022) investigated the use of bio-based polyurethane (PU) in OPC and RHPC mortars. Incorporating 15% PU enhanced flexural strength, reduced water absorption, and improved crack resistance, though compressive strength slightly decreased. PU proved effective in improving durability and watertightness for flexible applications.

Kirupakaran et al. (2023) studied bioconcrete with *Bacillus cereus* KOV15 and GGBS as partial cement replacements. The optimal mix (30% GGBS + 10% bacteria) improved compressive, tensile, and flexural strengths by 26.79%, 11.69%, and 21.3%, respectively, with enhanced resistance to acids and chlorides. Microanalysis showed increased CaCO₃ precipitation, enabling self-healing and higher densification, promoting sustainability through reduced cement use and microbial benefits.

Eskisar and Rahat (2025) evaluated mussel shell powder (MSP) as a soil stabilizer. Optimum MSP content (5% for recycled soils, 20% with cement) increased strength, reduced plasticity, and improved freeze–thaw durability by 40%. UPV tests confirmed strong correlation with compressive strength, highlighting MSP as a green, circular-economy stabilizer for sustainable ground improvement.

Niu et al. (2025) explored polyurethane-cement composites (PUC) for stabilizing talik in permafrost regions. Incorporating 10% PU enhanced freeze–thaw resistance, water stability, and reduced pore expansion. SEM revealed denser matrices and delayed hydration, confirming PUC as a climate-resilient reinforcement method for cold-region infrastructure.

Al Martini et al. (2025) assessed dredged dam materials (DDM) as partial aggregate replacements (0–10%) in cement grouts. A 10% DDM mix increased compressive strength by 40%, reduced shrinkage, and improved dimensional stability. Field trials showed crack-free performance over 11 months, validating DDM reuse as a sustainable circular economy practice.

Wang et al. (2024) developed mineral admixture–magnesium potassium phosphate cement (MA–MKPC) coatings for recycled aggregate concrete (RAC). A 10% MKPC treatment enhanced compressive strength, densified the interfacial transition zone (ITZ), and lowered porosity. The pre-coating without pre-curing method yielded the best performance, offering a low-carbon approach to improving RAC durability.

Yang et al. (2025) produced sintered sludge cement (SSC) using dredged sludge ash (SSA) as a supplementary material. Up to 30% SSA maintained strength and enhanced chloride resistance, while excessive SSA (50%) reduced strength. Microstructural tests confirmed progressive densification, showing SSA's potential as a partial cement replacement to reduce emissions, with dosage optimization essential for frost resistance.

Conventional OPC: Strengths and Limitations

OPC continues to be widely used due to its standardized performance, availability, and high early-age strength. Early hydration of OPC enables rapid strength gain, facilitating accelerated construction schedules. However, OPC exhibits high porosity, elevated calcium hydroxide content, and susceptibility to chemical attack, chloride ingress, and thermal cracking in massive structures. Eskisar and Rahat (2025) observed that OPC-based concretes demonstrated higher water absorption and lower resistance to freeze–thaw cycles compared to SCM-incorporated cements. These limitations motivate the incorporation of supplementary materials to improve long-term durability and sustainability.

Portland Pozzolana Cement (PPC)

PPC partially replaces OPC clinker with pozzolanic materials such as fly ash, volcanic ash, or rice husk ash. The pozzolanic reaction between silica and calcium hydroxide generates secondary calcium silicate hydrate (C–S–H), enhancing strength and densifying the pore structure. Literature reports that PPC generally exhibits moderate early-age strength but surpasses OPC at 28 days due to ongoing pozzolanic activity (Shao et al., 2025). PPC reduces heat of hydration, mitigating thermal cracking in massive elements, and improves resistance to sulphate attack and chloride ingress.

Blended Cements

Blended cements integrate multiple SCMs such as fly ash, GGBS, and silica fume in optimized proportions. Kirupakaran et al. (2023) demonstrated that a mixture of 30% GGBS and 10% microbial additives improved compressive, tensile, and flexural strengths by 26.79%, 11.69%, and 21.3%, respectively, while enhancing acid and chloride resistance. Wang et al. (2024) reported that mineral admixture–magnesium potassium phosphate cement (MA–MKPC) coatings on recycled aggregate concrete improved compressive strength, reduced porosity, and densified the interfacial transition zone (ITZ), confirming the benefits of SCM integration for durability enhancement.

Composite Cements

Composite cements combine multiple SCMs to achieve superior mechanical, durability, and sustainability performance. The complementary action of SCMs—fly ash for long-term strength, GGBS for chemical resistance, and silica fume for microstructural densification—enables a balanced performance. Al-Kahtani et al. (2022) observed that adding 15% bio-based polyurethane in OPC and RHPC mortars improved flexural strength, crack resistance, and water tightness. Niu et al. (2025) demonstrated enhanced freeze–thaw resistance and water stability in polyurethane-cement composites, indicating potential for cold-region and climate-resilient infrastructure.

Alternative SCMs and Sustainable Additives

Recent studies focus on incorporating industrial and bio-waste materials as SCMs to promote circular economy practices. Eskisar and Rahat (2025) reported that mussel shell powder (MSP) enhanced soil compressive strength and freeze–thaw durability by 40%. Al Martini et al. (2025) demonstrated that dredged dam materials could partially replace aggregates, improving compressive strength, dimensional stability, and shrinkage resistance. Yang et al. (2025) used dredged sludge ash in sintered sludge cement to improve chloride resistance and microstructural densification. These innovations reduce cement consumption, minimize waste, and promote sustainable concrete solutions.

Microstructural Insights

Microstructural analysis (SEM, XRD, porosity measurements) reveals that SCMs refine pore structure, increase C–S–H formation, and reduce calcium hydroxide content, collectively enhancing strength and durability. Studies report that composite cements achieve the densest microstructure among OPC, PPC, and blended cements, correlating with lower water absorption, reduced chloride penetration, and improved acid resistance.

Methodology

The present study was designed to systematically evaluate and compare the mechanical and durability performance of concrete prepared using four different cement types: Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), blended cement, and composite cement. The methodology was structured into stages, including material characterization, mix design, specimen casting, curing, and testing under controlled laboratory conditions, ensuring a fair comparison among the cement types.

Materials and Preliminary Testing

Cements were tested for initial and final setting times, specific gravity, and standard consistency according to IS standards. Fine and coarse aggregates were assessed through sieve analysis, specific gravity, and water absorption tests to confirm conformity with IS: 383-2016. Potable water and a superplasticizer were used to maintain workability without altering the water–cement ratio.

Mix Design and Specimen Preparation

An M40 grade concrete mix was designed following IS: 10262-2019 and IS: 456-2000 guidelines. The water–cement ratio was maintained at 0.45, and the same proportions were used for all cement types. Fresh concrete was tested for slump to evaluate workability. Specimens cast included 150 mm cubes for compressive strength, 150 × 300 mm cylinders for split tensile strength, and 100 × 100 × 500 mm prisms for flexural strength.

Curing and Testing

Specimens were demoulded after 24 hours and cured in water at $27 \pm 2^\circ\text{C}$. Testing was performed at 7, 14, and 28 days. Mechanical tests included compressive, split tensile, and flexural strength evaluations according to IS standards. Durability assessments comprised water absorption, acid resistance, and rapid chloride penetration tests (RCPT).

Data Analysis

All experimental data were statistically analyzed to determine mean values, variations, and performance trends. Comparative analysis of mechanical and durability results was conducted to identify cement types offering optimal strength, reduced permeability, and long-term durability. Microstructural observations supported performance trends, providing insights into pore structure and matrix densification.

This methodology ensures a systematic evaluation of cement types under identical conditions, enabling informed recommendations for sustainable and durable concrete construction, particularly in aggressive environmental exposures.

Environmental and Sustainability Considerations

The construction industry, particularly cement and concrete production, is a major contributor to global greenhouse gas emissions, accounting for approximately 8–10% of total CO₂ emissions worldwide. A substantial portion of these emissions arises from the production of clinker, the primary constituent of ordinary Portland cement (OPC), which involves high-temperature calcination of limestone. The chemical decomposition of calcium carbonate (CaCO₃) releases significant quantities of CO₂, while the thermal energy required for kiln operations further increases the carbon footprint. In this context, the development and utilization of composite cements incorporating supplementary cementitious materials (SCMs) offer a viable pathway toward environmentally sustainable construction practices.

Partial replacement of clinker with SCMs such as fly ash, ground granulated blast furnace slag (GGBS), metakaolin, silica fume, rice husk ash (RHA), and other industrial by-products can substantially reduce the embodied energy and CO₂ emissions of cementitious materials. Studies have reported that replacing 30–50% of clinker with SCMs can reduce CO₂ emissions by 20–40%, depending on the type and source of the SCM. Beyond emission reductions, the energy demand associated with clinker production is significantly lowered, contributing to a decrease in the overall environmental burden of cement production.

The integration of composite cements also supports the circular economy concept by valorizing industrial and agricultural wastes that would otherwise be discarded. Fly ash from thermal power plants, GGBS from steel manufacturing, marble sludge powder (MSP) from mining and processing operations, and dredged materials from waterways can be repurposed as SCMs, reducing landfill usage and mitigating the environmental impact associated with waste disposal. This approach aligns with sustainable resource management principles and promotes the development of low-carbon, eco-friendly infrastructure.

Moreover, composite cements often exhibit improved durability characteristics, including enhanced resistance to sulfate attack, alkali-silica reaction, and carbonation, which translates into longer service life and reduced material replacement over the lifecycle of a structure. Consequently, the life-cycle environmental impact, including raw material extraction, production, transportation, construction, and end-of-life disposal, is substantially minimized.

Global initiatives such as the United Nations Sustainable Development Goals (SDGs), the Paris Agreement on climate change, and various national-level green building codes emphasize the reduction of carbon emissions in the construction sector. The adoption of composite cements with optimized SCM content directly contributes to these goals by enabling low-carbon construction practices while maintaining or improving mechanical performance and durability.

In addition to environmental benefits, the use of locally available industrial by-products reduces reliance on natural resources, such as limestone, thus preserving ecosystems and minimizing land degradation. Life cycle assessment (LCA) studies have consistently shown that composite cements with high SCM content exhibit lower global warming potential, acidification, eutrophication, and resource depletion compared to conventional OPC.

In summary, the environmental and sustainability advantages of composite cement are multifaceted: they reduce clinker demand, lower energy consumption, mitigate CO₂ emissions, valorize industrial and agricultural waste, extend service life, and promote circular economy practices. These attributes make composite cements a critical component in the transition toward greener, more sustainable construction and infrastructure development worldwide.

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.

Compressive Strength

Compressive strength results are summarized in Table 1 and Figure 1. OPC exhibited the highest 7-day strength due to its rapid hydration, achieving early load-bearing capacity. However, at 28 days, PPC and blended cements surpassed OPC in strength development, benefiting from the slower pozzolanic reactions and refined microstructure. Composite cement showed the highest 28-day compressive strength, combining early strength gain from slag, long-term strength from fly ash, and pore refinement from silica fume. These findings align with previous studies showing SCMs improve long-term load resistance and durability.

Split Tensile and Flexural Strength

Similar trends were observed for tensile and flexural tests. OPC provided higher early-age strengths, whereas PPC, blended, and composite cements displayed superior strength at later ages due to continued pozzolanic and hydraulic reactions. Composite cement demonstrated the highest flexural performance, indicating better bonding and crack resistance, which is critical for structural members subjected to bending and tension.

Durability Performance

Water Absorption: OPC concrete had the highest absorption, indicating higher porosity. PPC and blended cements showed reduced absorption due to densification of the microstructure, while composite cement exhibited the lowest absorption, reflecting superior impermeability. **Acid Resistance:** Composite and blended cements retained higher strength after acid exposure, attributed to reduced $\text{Ca}(\text{OH})_2$ content and refined pore structure. **Chloride Penetration**

Comparative Analysis

Cement Type	Early Strength	28-Day Strength	Durability	Workability	Sustainability
OPC	High	Moderate	Moderate	Moderate	Low
PPC	Moderate	High	High	Good	Moderate
Blended Cement	Moderate	High	Very High	Good	High
Composite Cement	High	Very High	Very High	Excellent	Very High

Challenges and Future Research Directions

While supplementary cementitious materials (SCMs) and composite cements offer significant environmental and performance benefits, several technical, practical, and research-oriented challenges remain. Addressing these challenges is essential for broader adoption and reliable application of sustainable cementitious materials in modern construction.

Optimization of SCM Proportions

One of the most critical challenges in the development of SCM-based cements lies in determining the optimal replacement levels of clinker with SCMs. While increasing SCM content reduces embodied energy and carbon emissions, excessive replacement may adversely affect early-age properties, particularly compressive strength and setting time. For example, high volumes of fly ash or GGBS can lead to delayed hydration and slower strength gain in the first 7–28 days, potentially affecting construction schedules. Therefore, careful mix design, supported by experimental studies and predictive modeling, is crucial to achieve a balance between sustainability and mechanical performance. Future research should focus on developing performance-based mix optimization techniques, including multi-objective optimization frameworks that consider early-age strength, durability, and environmental impact simultaneously.

Field Durability Assessment

Laboratory studies on SCM-based cements provide valuable insights into their mechanical and durability characteristics; however, long-term field performance under real-world environmental conditions is less understood. Factors such as temperature fluctuations, humidity variations, freeze–thaw cycles, carbonation, chloride ingress, and sulfate attack can significantly influence material behavior over decades. Current standards and durability tests often do not fully capture these complex interactions. Therefore, extended field trials and in-situ monitoring of structures built with composite cements are essential. Integration of non-destructive testing techniques, digital sensors, and smart monitoring systems can help generate reliable long-term performance data and inform future standards and guidelines.

Emerging Materials and Novel SCMs

In addition to conventional SCMs like fly ash and GGBS, research into bio-based materials (e.g., rice husk ash, sugarcane bagasse ash, bamboo ash) and nanomaterials (e.g., nano-silica, graphene oxide, carbon nanotubes) is gaining momentum. These materials can enhance hydration kinetics, microstructure, and durability while further reducing environmental impacts. However, the introduction of such materials raises several challenges, including variability in chemical composition, potential health risks, handling complexities, and lack of standardized testing protocols. Future research should prioritize systematic evaluation of these emerging materials, establish standardized characterization methods, and assess their long-term compatibility with conventional cementitious matrices.

Climate Resilience and Extreme Environment Performance

With the increasing frequency of extreme weather events and climate-induced environmental stressors, assessing the resilience of SCM-based cements under adverse conditions is critical. Freeze–thaw cycles, sulfate-rich soils, seawater exposure, and acidic environments can compromise the durability of concrete structures. While SCMs can improve resistance to some of these effects (e.g., reduced permeability and enhanced sulfate resistance), systematic studies on multi-factorial environmental exposure, especially in marine and coastal regions, are still limited. Future investigations should focus on accelerated aging tests, combined stress testing, and predictive durability modeling to ensure that composite cements can withstand long-term climate-induced challenges.

Standardization and Regulatory Frameworks

The lack of uniform standards and regulatory guidelines for SCM-based cements often limits their adoption in large-scale infrastructure projects. Differences in material quality, regional availability, and performance variability require region-specific guidelines for mix design, quality control, and testing. Research and collaboration between academia, industry, and standardization bodies are necessary to develop robust codes and specifications, ensuring safe and reliable use of composite cements worldwide.

Life-Cycle Assessment and Sustainability Metrics

Although composite cements are inherently more sustainable than OPC, comprehensive life-cycle assessment (LCA) studies that consider all phases—from raw material extraction to end-of-life disposal—are still limited. Future research should integrate environmental, economic, and social dimensions of sustainability, including carbon footprint, energy consumption, resource circularity, and cost-effectiveness, to provide a holistic understanding of SCM-based cements' true sustainability benefits.

Conclusion:

The experimental investigation comparing OPC, PPC, blended, and composite cements under identical mix proportions and curing conditions provides the following conclusions:

Mechanical Performance: OPC exhibits higher early-age compressive, tensile, and flexural strengths due to rapid hydration. However, PPC, blended, and composite cements outperform OPC at later ages (28 days) as a result of continued pozzolanic and hydraulic reactions. Composite cement demonstrates the highest long-term strength due to synergistic effects of multiple SCMs.

Durability: OPC concrete shows higher porosity, water absorption, and susceptibility to chemical attack. The incorporation of SCMs in PPC, blended, and composite cements significantly reduces permeability, enhances acid and chloride resistance, and improves microstructural densification. Composite cement provides superior impermeability and durability, making it ideal for aggressive environmental exposures.

Workability: SCM-containing cements improved fresh concrete flowability, with composite cement exhibiting the best slump and handling characteristics due to refined particle packing and micro-filler effects.

Sustainability: Partial replacement of clinker with fly ash, slag, and silica fume reduces carbon footprint and embodied energy, supporting environmentally responsible construction without compromising strength and durability.

Overall, the study demonstrates that composite cement offers the best combination of early and long-term strength, durability, and sustainability. The findings advocate the use of SCM-based cements for eco-friendly, resilient, and durable concrete structures, particularly in marine, sulphate-rich, and other aggressive environments.

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