

## A Review of Cement and Alternative Cementitious Materials in the Construction Industry

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**Abstract:** The increasing environmental impact of Ordinary Portland Cement (OPC) production, which accounts for a significant portion of global CO<sub>2</sub> emissions, has led to a growing interest in Alternative Cementitious Materials (ACMs) as sustainable alternatives. This literature review critically evaluates the properties, performance, and environmental benefits of ACMs, including fly ash, silica fume, ground granulated blast furnace slag (GGBS), metakaolin, and rice husk ash. A systematic search was conducted, sourcing 70 articles, of which 43 met the inclusion criteria. The review highlights the chemical, physical, and mechanical properties of these materials, their impact on concrete durability, and their potential to reduce the carbon footprint of construction. Challenges such as inconsistent quality, lack of standardized mix designs, and regulatory barriers are discussed, along with recommendations for overcoming these obstacles through innovation and policy support. This review provides a comprehensive understanding of ACMs' role in advancing sustainable construction practices, offering insights into their practical applications and future research directions.

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### 1. INTRODUCTION

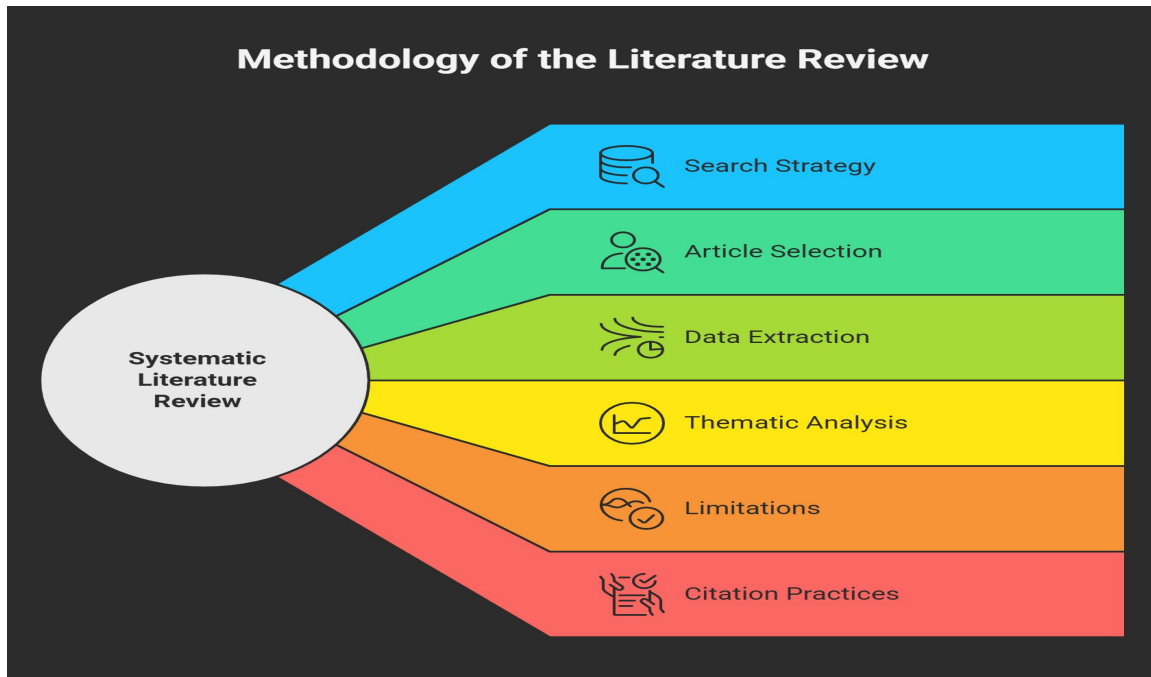
Cement is a critical material in the construction industry, with Ordinary Portland Cement (OPC) being the most widely used binder despite its significant environmental impact, contributing to 7–8% of global CO<sub>2</sub> emissions (Burris et al., 2015). In response, Alternative Cementitious Materials (ACMs) such as fly ash, silica fume, GGBS, metakaolin, and agricultural waste have been explored for their potential to reduce the carbon footprint, promote recycling, and improve concrete properties (Abdullah et al., 2021; Da Silva et al., 2025; Chandar & Santhosh, 2022). However, challenges such as inconsistent quality, lack of standardized mix designs, and limited regulatory frameworks hinder widespread adoption (Bano et al., 2022).

### II. METHODOLOGY OF THE REVIEW

This systematic literature review is aimed to assess the properties and potential applications of Alternative Cementitious Materials (ACMs) in concrete production. A comprehensive search strategy was employed, sourcing 70 articles from academic databases using relevant keywords. After screening for relevance based on predefined criteria, 43 articles were selected for inclusion. Key details such as study methodology, sample size, and findings were extracted and critically analyzed. The studies were synthesized through thematic analysis to identify trends and gaps, with limitations such as publication bias and language restrictions acknowledged. All sources were properly cited to ensure transparency and reproducibility. Fig.1 illustrates the key components of the systematic

literature review process, including Search Strategy, Article Selection, Data Extraction, Thematic Analysis,

Limitations, and Citation Practices, each represented by distinct colored sections.



**Fig.1: Methodology of the Literature Review**

### Ordinary Portland Cement (OPC): Composition and Limitations

Ordinary Portland Cement (OPC) is primarily composed of tricalcium silicate ( $\text{Ca}_3\text{SiO}_5$ ,  $\text{C}_3\text{S}$ ), dicalcium silicate ( $\text{Ca}_2\text{SiO}_4$ ,  $\text{C}_2\text{S}$ ), tricalcium aluminate ( $\text{Ca}_3\text{Al}_2\text{O}_6$ ,  $\text{C}_3\text{A}$ ), and tetracalcium aluminoferrite ( $\text{Ca}_4\text{Al}_2\text{Fe}_2\text{O}_{10}$ ,  $\text{C}_4\text{AF}$ ). Among these,  $\text{C}_3\text{S}$  plays a major role in early strength development,  $\text{C}_2\text{S}$  contributes to long-term strength, while  $\text{C}_3\text{A}$  and  $\text{C}_4\text{AF}$  influence the setting time and heat of hydration, and susceptibility to sulfate attack (Duchesne, 2020). The hydration of OPC forms calcium silicate hydrate (C-S-H), responsible for strength, and calcium hydroxide (CH), which can affect durability due to carbonation (Duchesne, 2020). Mechanically, OPC concrete exhibits excellent

compressive strength but is prone to brittleness and cracking under tensile or flexural stress (Gupta et al., 2016), and while it offers good workability and durability under normal conditions, it deteriorates under harsh environments (Ewert et al., 2024). The environmental footprint of OPC is significant due to the  $\text{CO}_2$  emissions from limestone calcination, with approximately 0.9 tons of  $\text{CO}_2$  released per ton of OPC produced, alongside high energy use (Gupta et al., 2016; Gupta et al., 2021). Efforts to reduce this impact have led to alternative cementitious materials (ACMs) like fly ash, slag, and natural pozzolans, which reduce  $\text{CO}_2$  emissions and enhance durability, thus supporting sustainability in construction (Gupta, 2021; Ewert et al., 2024; Guo et al., 2022). Fig.2 presents a balanced overview of the advantages and limitations of Ordinary Portland Cement.



Fig. 2: Pros and Cons of Ordinary Portland Cement (OPC)

### Alternative Cementitious Materials (ACMs)

Alternative Cementitious Materials (ACMs) have been developed as substitutes or supplements to Ordinary Portland Cement (OPC) in concrete, driven by the need to reduce the environmental impact associated with cement production. Cement manufacturing is a significant contributor to  $CO_2$  emissions, primarily due to the decarbonation of limestone and energy-intensive processes (Duchesne, 2020). Fly ash, a by-product of coal combustion in power plants, is primarily composed of silica, alumina, and iron oxide, with Class F fly ash being pozzolanic and Class C fly ash exhibiting both pozzolanic and cementitious properties, improving workability and long-term strength (Duchesne, 2020; Ewert et al., 2024). Silica fume, a by-product of silicon and ferrosilicon alloy production, is highly reactive due to its fine particles, enhancing early-age strength and durability, especially in marine environments (Gupta et al., 2016; Hamad et al., 2021). Ground Granulated

Blast Furnace Slag (GGBS), produced from cooling molten iron slag, offers both pozzolanic and cementitious properties, improving concrete's resistance to chemical attacks and reducing heat during hydration (Guo et al., 2022; Gupta, 2021). Metakaolin, derived from kaolin clay, reacts with calcium hydroxide to form C-S-H gel, enhancing strength and durability, and improving resistance to chloride ingress and sulfate attack (Gupta et al., 2016; Hamad et al., 2021). Rice husk ash (RHA), rich in silica, contributes to improved workability, reduced permeability, and enhanced resistance to chemical degradation, utilizing agricultural waste (Gupta et al., 2016; Guo et al., 2022). Natural pozzolans, such as volcanic ash and calcined clays, undergo pozzolanic reactions with lime, improving concrete's strength, durability, and resistance to chemical attacks (Gupta et al., 2016; Gupta, 2021). Alkali-activated binders and geopolymers, formed by activating aluminosilicate materials with alkaline solutions, exhibit high mechanical strength and durability, along with a lower

carbon footprint, offering an eco-friendly alternative to traditional cement (Guo et al., 2022). Fig.3 highlights

various alternative cementitious materials and their benefits in concrete applications.

### Alternative Cementitious Materials

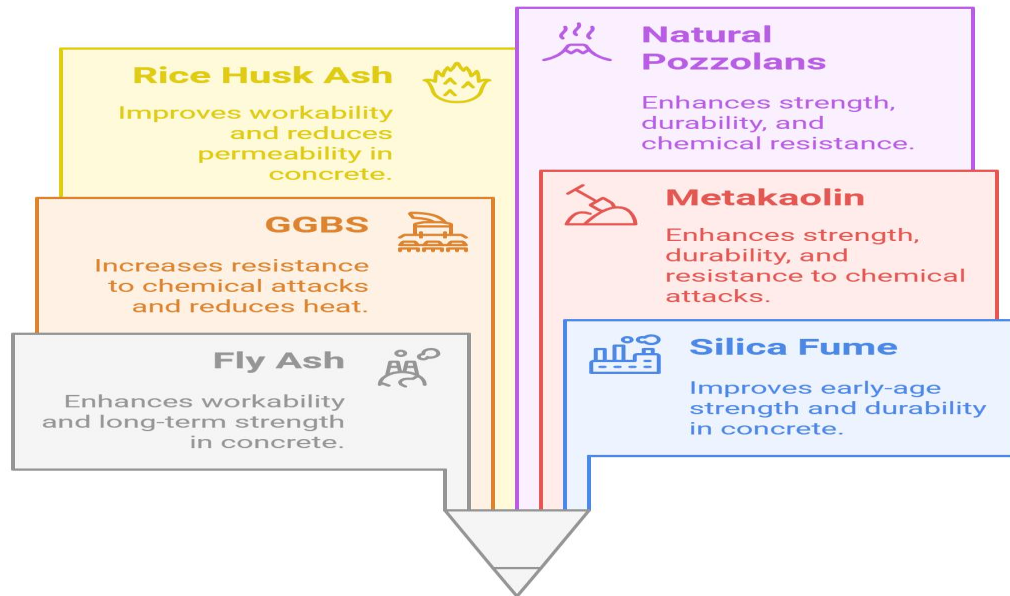


Fig. 3: Comparative Analysis of OPC and ACMs

Ordinary Portland Cement (OPC) is energy-intensive and a major contributor to global CO<sub>2</sub> emissions, while Alternative Cementitious Materials (ACMs) such as fly ash, silica fume, Ground Granulated Blast Furnace Slag (GGBS), metakaolin, rice husk ash (RHA), and geopolymers offer more sustainable options by reducing CO<sub>2</sub> emissions. Fly ash enhances long-term strength and durability, reducing permeability and improving resistance to sulfate attack and alkali-silica reactions (Isaksson et al., 2023; Jhatial et al., 2023). Silica fume improves strength and reduces permeability (Jwaida et al., 2023), while GGBS enhances resistance to aggressive chemical environments ((Awad et al.,

2022); Memon, 2022). Metakaolin and RHA improve durability and strength, reducing shrinkage and refining microstructures (Milović et al., 2022). Geopolymers, utilizing industrial by-products, offer excellent strength, durability, and sustainability (Mushtaq et al., 2025). These materials can replace up to 30-50% of OPC without significantly compromising strength, with geopolymers replacing OPC entirely (Isaksson et al., 2023; Jwaida et al., 2023; Memon, 2022; Milović et al., 2022; Mushtaq et al., 2025). Fig.4 presents a comparative analysis of cementitious materials, including OPC, Fly Ash, Silica Fume, GGBS, Metakaolin & RHA, and Geopolymers.

| Characteristic            | OPC      | Fly Ash  | Silica Fume          | GGBS                    | Metakaolin & RHA | Geopolymers |
|---------------------------|----------|----------|----------------------|-------------------------|------------------|-------------|
| CO <sub>2</sub> Emissions | High     | Low      | Low                  | Low                     | Low              | Low         |
| Long-Term Strength        | Standard | Enhanced | Improved             | Standard                | Improved         | Excellent   |
| Durability                | Standard | Enhanced | Reduced Permeability | Resistance to Chemicals | Improved         | Excellent   |
| OPC Replacement           | 0%       | 30-50%   | 30-50%               | 30-50%                  | 30-50%           | 100%        |

Fig.4: Cementitious Materials Comparison

### Performance, Sustainability, and Challenges of Supplementary Cementitious Materials

Supplementary cementitious materials (SCMs) significantly influence concrete's fresh properties, mechanical strength, durability, and environmental footprint. Calcined palygorskite improves workability due to enhanced dispersion based on fineness and dosage (Poussardin et al., 2022), while lithium slag-based binders optimized through Box–Behnken designs provide controlled setting times and consistency (Shao et al., 2024). SCMs such as ceramic waste powder and harvest residue ash from Vojvodina enhance compressive and tensile strengths through pozzolanic activity and microstructural densification (Šupić et al., 2022). Reclaimed asphalt pavement (RAP) also yields satisfactory strength when incorporated with cementitious binders (Tiza, Agunwamba, & Okafor, 2024). Durability improvements, including reduced permeability and enhanced sulfate and acid resistance, are observed with harvest residue ash, ceramic waste, and RAP (Šupić et al., 2022; Tiza et al., 2024). SCMs refine the cement matrix's microstructure and hydration mechanisms, as shown through SEM and EDS analyses (Poussardin et al., 2022; Ruiz-Agudo & Cölfen, 2024), while oxide composition studies support the compatibility of RAP and aggregates in cement matrices (Tiza, Okafor, & Agunwamba, 2025). Environmentally, SCM use reduces embodied carbon and energy consumption, as reported in LCA studies involving PET, glass waste, and industrial by-products (Zapała-Sławeta, Mazurek, & Woś, 2023; Zhang et al., 2024), with potential emissions reductions of up to 30% when scaled. Economically, optimized designs using local recycled materials like RAP can reduce costs while maintaining strength (Tiza, Agunwamba, & Okafor, 2025). Despite these benefits, challenges persist, including high variability in SCM composition (Duchesne, 2020; Guo, 2022; Milović et al., 2022), limited mix design protocols (Guo et al., 2022; Memon, 2022), and poor field translation of laboratory models (Shao et al., 2024; Tiza, Okafor, & Agunwamba, 2025). SCM-admixture compatibility remains uncertain (Gupta et al., 2016; Hartwich, Pritzel, & Killian, 2022), and regulatory barriers hinder adoption despite proven mechanical and environmental performance, particularly in Sub-Saharan Africa and informal markets (Ewert et al., 2024; Isaksson et al., 2023). Although geopolymer binders offer sustainable alternatives, their mainstream use is limited due to a lack of unified design codes (Jwaida et al., 2023; Mushtaq et al., 2025).

### Future Perspectives and Research Needs

Advancing alternative cementitious materials (ACMs) requires the development of robust standards and region-specific guidelines to ensure consistent quality, regulatory approval, and integration into construction practices (Duchesne, 2020; Milović, Šupić, Malešev, & Radonjanin, 2022). Standardized procedures, including technical datasheets and performance-based specifications, are essential for emerging supplementary cementitious materials (SCMs) like calcined palygorskite to ensure safety and reproducibility (Poussardin et al., 2022). Hybrid systems blending traditional cement with waste-derived materials such as ceramic powders, fly ash, and slag have shown synergistic improvements in strength, emissions reduction, and cost-efficiency (Gupta, 2021; Jhatial, Nováková, & Gjerløw, 2023; Signorini et al., 2022). Innovations incorporating nanotechnology and bio-derived additives, like TiO<sub>2</sub> nanotube arrays for self-cleaning concrete (Hartwich, Pritzel, & Killian, 2022) and genetically optimized banana skin powder in bio-cement (Hasibuan, Prayuda, & Muhathir, 2023), further enhance performance. Nonetheless, these technologies demand long-term performance studies, scalability assessments, and lifecycle evaluations. Policy integration remains key to practical adoption, as emphasized by Jwaida et al. (2023) regarding geopolymer use in green infrastructure, and Isaksson et al. (2023), who identified policy and capacity gaps hindering SCM uptake in Sub-Saharan Africa. Future efforts must therefore extend beyond laboratory work to include implementation frameworks, stakeholder engagement, and policy alignment.

### IV. CONCLUSION

The review of Alternative Cementitious Materials (ACMs) highlights significant advancements in the development and application of sustainable substitutes for traditional Portland cement, including lignocellulosic biomass, fly ash, ceramics, and geopolymers. These materials demonstrate comparable or superior performance in terms of strength, durability, and environmental benefits. Despite challenges like material variability, admixture compatibility, and regulatory limitations, the feasibility of ACMs is supported by their widespread availability and lower carbon footprint. Emerging innovations such as hybrid binders, nanomaterials, and bio-cementation further enhance their potential. For meaningful adoption, standardized guidelines, robust quality control, and supportive policy frameworks are essential. Prioritizing ACMs in construction, particularly in developing regions, through education, pilot programs, and

industry partnerships, can drive a sustainable shift in infrastructure development.

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