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A Systematic Review on the Mechanical and Environmental Performance of Concrete with Supplementary cementitious Materials

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ABSTRACT

This study presented a comprehensive review of sustainable concrete that incorporated supplementary cementitious materials (SCMs). It evaluated the impact of SCMs on the durability and compressive strength of concrete, while also considering the environmental implications of their use. The findings highlighted the potential benefits of utilizing SCMs in concrete production and emphasized their role in enhancing performance and reducing the carbon footprint of construction materials.

1. Introduction

1.1. Background on Concrete Production

Concrete ranks among the most widely used construction materials worldwide, forming the foundation of modern infrastructure (Althoey et al., 2023). Its roots stretch back over 8,000 years, evolving from simple natural mixes into sophisticated engineered composites that support diverse architectural and civil engineering projects (Samad & Shah, 2017). Cement acts as the key ingredient in concrete, binding aggregates together and delivering strength and durability (Kowshika et al., 2024). However, cement production generates substantial greenhouse gas emissions roughly one ton of CO_2 per ton of cement making it a major factor in climate change (Samad & Shah, 2017).

The demand for concrete has risen sharply due to rapid urban growth and population increases (Kowshika et al., 2024). This surge calls for fresh strategies to boost concrete's performance while reducing its environmental impact. Traditional mix designs depend largely on a specific water-cement ratio to meet strength requirements, but this approach can stifle innovation in achieving better sustainability and performance (Valenzuela-Leyva et al., 2025). That's why the field has embraced supplementary cementitious materials (SCMs) like fly ash (FA), ground granulated blast furnace slag (GGBS), and silica fume (SF) (Zhang et al., 2019). These industrial by-products partly replace cement and boost concrete's mechanical strength and durability (Ismail et al., 2024). Studies show that adding SCMs can improve compressive strength, lower vulnerability to alkali-silica reaction (ASR), and enhance resistance to environmental stresses (Jing et al., 2025). For example, fly ash from coal combustion improves workability and cuts down the cement quantity in mixes. Likewise, GGBS strengthens concrete over time via pozzolanic reactions within its matrix (Jing et al., 2025).

Furthermore, the industry increasingly turns to recycled SCMs, supporting circular economy goals that focus on waste reduction and sustainability in construction (Jing et al., 2025). By reusing materials that might otherwise go to landfills, the sector curbs resource use and transportation emissions tied to conventional aggregates (Adak et al., 2025). Advanced chemical admixtures complement these trends by allowing lower water content without sacrificing performance (Lahre et al., 2025). This fits well with modern practices aimed at

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reducing carbon footprints throughout construction materials' life cycles (Özkılıç et al., 2025). Recent research on innovative concrete formulations combining SCMs and traditional methods highlights the importance of sustainable production techniques not only for enhancing structural integrity but also for tackling pressing environmental challenges (Hashim et al., 2025).

1.2. Importance of Sustainability in Construction

The construction sector stands out as a major source of environmental harm, contributing heavily to global carbon emissions (Althoey et al., 2023). According to Althoey et al. (2023), the cement manufacturing process alone accounts for about 5% to 8% of worldwide output. This reality has sparked a growing recognition of the need to adopt greener methods, especially as concrete demand climbs due to ongoing urban growth and infrastructure needs (Samad & Shah, 2017). Sustainable construction aims to cut waste and environmental damage while improving how efficiently resources are used throughout a building material's life (Mohamad et al., 2022).

Introducing eco-friendly steps into concrete production can dramatically shrink its carbon footprint and boost resource conservation (Mohamad et al., 2022). For example, Supplementary Cementitious Materials (SCMs) such as fly ash, ground granulated blast-furnace slag (GGBS), and silica fume reduce the energy tied to cement and make concrete stronger and longer-lasting (Zhang et al., 2019). Using these materials as partial cement substitutes leads to better structural results with fewer greenhouse gases released (Zhang et al., 2019). Another key tactic for sustainability is recycling old concrete as aggregate for new mixes, which helps relieve pressure on natural resources (Jing et al., 2025). This practice also cuts landfill volumes from demolished buildings. Jing et al. (2025) highlight how recycled aggregates lessen environmental harm and support circular economy ideas in city development projects.

The push for sustainability goes beyond immediate environmental gains it offers lasting economic benefits too (Ismail et al., 2024). Ismail et al. (2024) note that optimizing concrete with recycled aggregates can slash expenses linked to buying raw materials and hauling away waste. Embracing sustainable approaches sparks innovation in construction, yielding more durable buildings that withstand climate stresses while keeping attractive designs (Ismail et al., 2024). Furthermore, adopting green methods reflects rising ethical awareness among construction stakeholders (Althoey et al., 2023). Growing public concern about climate change raises the bar for eco-friendly actions from both producers and buyers. More industry players see that choosing low-carbon options not only meets regulations but also boosts reputations and earns customer trust through responsible branding (Althoey et al., 2023).

1.3. Overview of Supplementary Cementitious Materials (SCMs)

Supplementary Cementitious Materials (SCMs) enhance concrete's properties and sustainability by replacing part of traditional Portland cement (Mohamad et al., 2022). They fall into two groups: industrial by-products and natural pozzolans (Mohamad et al., 2022). Industrial by-products include fly ash, ground-granulated blast-furnace slag (GGBS), silica fume, and metakaolin (Mohamad et al., 2022). Fly ash comes from burning coal in power plants, while GGBS is a by-product of iron production (Jing et al., 2025). Natural pozzolans like rice husk ash (RHA) and volcanic ash form cement-like compounds when mixed with lime (Jing et al., 2025).

Using SCMs reduces concrete's carbon footprint. Cement production causes about 7% of global emissions (Jing et al., 2025). Replacing cement with SCMs lowers greenhouse gas emissions and improves concrete performance (Jing et al., 2025). Their effectiveness depends on type and amount. Adding 5-30% SCMs usually boosts strength and durability (Zhang et al., 2019). Fly ash improves strength and workability but may become scarce as coal power declines (Zhang et al., 2019). GGBS enhances resistance to thermal cracking and produces fewer emissions (Zhang et al., 2019). Silica fume raises compressive strength but needs careful use to avoid shrinkage (Liu et al., 2025).

2. Literature Review

2.1. Historical Use of SCMs in Concrete

Supplementary Cementitious Materials (SCMs) have a long-standing tradition in concrete production, reflecting ongoing efforts to boost sustainability in construction (Zhang et al., 2019). Traditional SCMs like fly ash and ground granulated blast-furnace slag (GGBS) have been key players for decades. Fly ash found its way into concrete as early as the 1930s due to its positive effects on durability and strength (Zhang et al., 2019). Meanwhile, GGBS has been valued since at least the late 18th century for its pozzolanic qualities (Zhang et al., 2019).

The adoption of SCMs has expanded over the years because they help reduce the environmental impact tied to cement production. Portland cement manufacturing generates roughly one ton of for every ton produced (Samad & Shah, 2017). Swap some Portland cement for SCMs such as fly ash or GGBS lowers the carbon footprint while improving concrete's durability and compressive strength (Cyr, 2013). Beyond environmental benefits, SCMs improve practical aspects of concrete. Their pozzolanic reactions combine with calcium hydroxide from hydration to form a denser microstructure (Ranger, 2023). Still, relying heavily on traditional SCMs raises concerns about supply shortages (Ranger, 2023).

2.2. Recent Advances in SCM Technology

Recent breakthroughs in SCMs have raised the bar for concrete's sustainability and performance (Althoey et al., 2023). One exciting advancement involves alternative materials like volcanic ash and metakaolin blends (Liu et al., 2023). Although volcanic ash may slightly lower compressive strength, studies show it improves resistance to ASR and cuts chloride penetration (Liu et al., 2023). The use of recycled SCMs is also gaining ground; for example, combining fly ash with rhyolite aggregates has helped reduce ASR risks (Valenzuela-Leyva et al., 2025). Additionally, fly ash boosts electrical resistivity and lowers chloride permeability in eco-friendly mixes (Valenzuela-Leyva et al., 2025). Nanotechnology is also carving out an innovative role, as adding nanoparticles enhances calcium silicate hydrate (C-S-H) gel formation, reducing pore connectivity and improving water resistance (Cyr, 2013).

3. Methodology

3.1 Review Protocol

This study follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and systematic selection of relevant literature.

3.2 Search Strategy

The literature search was conducted using the following databases:

- Scopus
- Web of Science
- Science Direct
- Google Scholar

The search covered publications between 2010 and 2025.

3.3 Inclusion and Exclusion Criteria

Inclusion Criteria:

- Peer-reviewed journal articles
- Experimental studies on SCMs
- Studies reporting mechanical or environmental performance
- English language

Exclusion Criteria:

- Non-peer-reviewed sources
- Conference abstracts without full data
- Wikipedia and non-academic sources

3.4 Data Extraction and Synthesis:

Data were extracted regarding:

- Type of SCM
- Replacement percentage
- Compressive strength results
- Durability indicators
- CO_2 emissions reduction

A qualitative comparative synthesis was performed.

3.5 Study Selection Process

The initial database search yielded 312 records. After removing 47 duplicate articles, 265 studies were screened based on titles and abstracts. Following the screening process, 118 full-text articles were assessed for eligibility. Based on the predefined inclusion and exclusion criteria, 54 peer-reviewed studies were included in the final qualitative synthesis. The study selection process followed the PRISMA framework to ensure transparency and reproducibility. The study selection procedure is illustrated in Figure 1.

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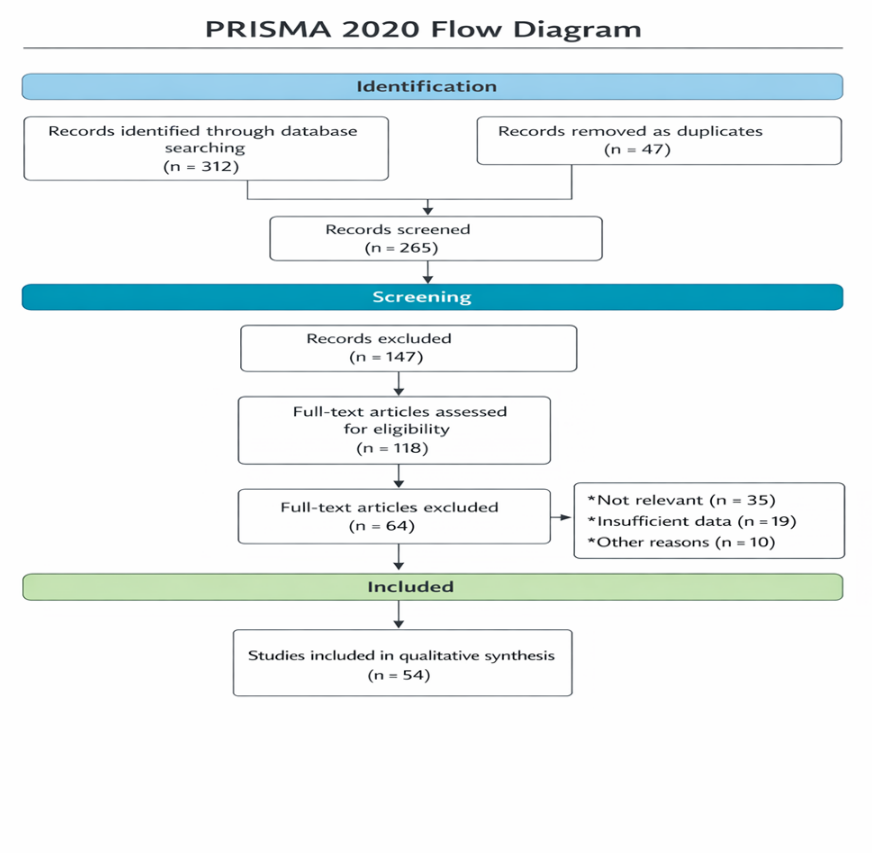

Figure 1. PRISMA flow diagram of study selection process

Table 1: Comparative Environmental and Cost Performance of SCM-Based Mixes

Mix ID	Mix Composition	Cement Content (kg/m³)	CO_2 Emissions (kg/m³)	CO_2 Reduction (%)	Total Cost (USD/m³)	Cost Reduction (%)	Reference
OPC-Control	100% OPC	450	418.5	–	37.75	0	Kowshika et al. (2024)
OPC + NA	OPC + 1.2% additive	400	372.0	11.1	38.89	-3.0	Kowshika et al. (2024)
OPC + GGBS	50% OPC + 50% GGBS	225	229.5	45.2	33.44	11.4	Kowshika et al. (2024)
OPC + PFA (20%)	360 OPC + 90 PFA	360	342.9	18.1	36.24	4.0	Kowshika et al. (2024)
OPC + PFA (35%)	260 OPC + 140 PFA	260	254.4	39.2	35.89	4.9	Kowshika et al. (2024)

Table 2: Effect of SCM Type and Replacement Level on Compressive Strength

SCM Type	Replacement (%)	Early Strength (7 days)	28-day Strength	Long-Term Strength	Key Observation	Reference
Fly Ash (FA)	20–35%	Reduced	Comparable / Slightly higher	Significantly higher over time	Slower early hydration	Cyr (2013); Zhang et al. (2019)
GGBS	30–50%	Slightly reduced	Improved	Higher long-term strength	Enhanced pozzolanic reaction	Zhang et al. (2019)
Silica Fume (SF)	5–15%	Increased	Significantly increased	High durability	Dense microstructure	Valenzuela-Leyva et al. (2025)

Volcanic Ash	10%	Slight reduction	+5.6% increase	Improved durability	ASR resistance improved	Abutaqa et al. (2024)
Rice Husk Ash (RHA)	10–20%	Moderate	Improved	Enhanced durability	Improved pore refinement	Jing et al. (2025)

Table 3: Durability Performance of SCM-Based Concrete

SCM	Chloride Resistance	ASR Resistance	Water Absorption	Electrical Resistivity	Microstructure Effect	Reference
Fly Ash	Improved	Reduced ASR	Reduced	Increased	Refined pore structure	Zhang et al. (2019); Valenzuela-Leyva et al. (2025)
GGBS	High resistance	Improved	Reduced	Increased	Dense C-S-H formation	Zhang et al. (2019)
Silica Fume	Very high	Strong mitigation	Very low	High	Very dense matrix	Valenzuela-Leyva et al. (2025)
Volcanic Ash	Moderate	High resistance	Reduced	Moderate	Pozzolanic reaction	Liu et al. (2023)
Waste Glass Powder	Improved	Moderate	Reduced	Improved	Filler + Pozzolanic effect	Adak et al. (2025)

Table 4: Environmental Sustainability Comparison of Major SCMs*

SCM	Industrial Source	CO_2 Reduction Potential	Energy Saving	Sustainability Advantage	Limitation
Fly Ash	Coal combustion	High (20–40%)	High	Waste reutilization	Supply declining globally
GGBS	Steel industry	Very high (40–50%)	High	Long-term durability	Regional availability
Silica Fume	Silicon production	Moderate	Moderate	High strength performance	Higher cost
Rice Husk Ash	Agricultural waste	Moderate	High	Renewable source	Quality variability
Waste Glass Powder	Recycled glass	Moderate	High	Circular economy support	Alkali content concerns

*Sources: Zhang et al. (2019); Jing et al. (2025); Adak et al. (2025); Althoey et al. (2023)

4. Results and discussion

4.1. Impact on Compressive Strength

Previous studies reported that the incorporation of SCMs significantly affects compressive strength (Makwana et al., 2025). Natural Volcanic Tuffs (NVTs) at 10% replacement can increase strength by around 5.6% after 28 days (Abutaqa et al., 2024). Mixtures with 10% silica fume exhibit the greatest strength gains and better resistance to chloride intrusion (Valenzuela-Leyva et al., 2025). High-volume fly ash concretes may show lower early strength but can gain over 120% strength over ten years (Cyr, 2013).

4.2. Assessment of Durability Factors

Research demonstrates that SCMs improve durability by resisting ASR, chloride penetration, and water absorption (Zhang et al., 2019; Valenzuela-Leyva et al., 2025). SCMs improve concrete microstructure by promoting more C-S-H gel during hydration, which fills pores and makes the matrix denser (Ranger, 2023). Lower water absorption means higher density and better freeze-thaw resistance (Zhang et al., 2019).

4.3. Environmental and Cost Analysis

Replacing Portland cement with SCMs leads to meaningful reductions in CO_2 emissions output (Valenzuela-Leyva et al., 2025). Table 1 illustrates the emission and cost reductions achieved across various mix series. Table 2 summarizes the comparative effects of SCMs on compressive strength based on published literature.x series. As shown in Table 2, silica fume demonstrates the most significant improvement in early-age compressive strength due to its high pozzolanic reactivity and micro-filling effect. In contrast, fly ash tends to reduce early strength but contributes substantially to long-term strength development through delayed hydration reactions. GGBS provides balanced performance, enhancing durability and long-term mechanical properties. These findings highlight an important trade-off between early strength requirements and long-term sustainability performance.

Table 3 indicates that most SCMs significantly enhance durability performance by refining pore structure and reducing chloride permeability. Silica fume provides the highest resistance to chloride ingress, while fly ash and GGBS effectively mitigate alkali–silica reaction (ASR). However, performance variability may occur depending on curing conditions, replacement ratios, and material quality.

As presented in Table 4, industrial by-product SCMs such as GGBS and fly ash offer the highest potential for CO_2 reduction due to substantial clinker replacement. Nevertheless, the declining availability of fly ash in regions transitioning away from coal-fired power plants may limit its long-term applicability. Agricultural and recycled waste-based SCMs present promising alternatives but may require improved quality control and standardization.

5. Conclusions

This systematic review demonstrates that supplementary cementitious materials (SCMs) significantly enhance the mechanical, durability, and environmental performance of concrete. While materials such as silica fume improve early-age strength, fly ash and GGBS contribute more effectively to long-term strength development and durability enhancement.From an environmental perspective, SCM incorporation substantially reduces CO_2 emissions by decreasing clinker content and promoting circular economy principles through industrial waste reutilization. However, trade-offs exist between early strength development, long-term performance, cost variability, and material availability. Future research should focus on performance-based standardization, optimization of multi-SCM blends, and integration of emerging technologies such as nanomaterial to further advance sustainable concrete design.

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