

## DEVELOPMENT OF SUSTAINABLE HIGH-PERFORMANCE CONCRETE USING SUPPLEMENTARY CEMENTITIOUS MATERIALS: EVALUATION OF MECHANICAL STRENGTH, DURABILITY, AND ENVIRONMENTAL PERFORMANCE

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<https://doi.org/10.5281/zenodo.23256189>

### Abstract

The rapid expansion of the construction sector has increased demand for concrete while intensifying concerns regarding the environmental impact of Portland cement production. High-performance concrete (HPC) provides superior mechanical strength and durability, but its conventional production may require high cement contents, resulting in increased embodied energy and carbon dioxide emissions. The incorporation of supplementary cementitious materials (SCMs), including fly ash, ground granulated blast-furnace slag (GGBFS), silica fume, metakaolin, and other industrial or agricultural by-products, provides an effective pathway for developing more sustainable high-performance concrete. This article evaluates the influence of SCM incorporation on the mechanical, durability, and environmental performance of HPC through a literature-based analytical approach. Particular attention is given to compressive strength, flexural performance, permeability, chloride resistance, carbonation, shrinkage, and embodied carbon. The reviewed literature demonstrates that appropriately selected and proportioned SCMs can reduce Portland cement consumption while maintaining or improving long-term mechanical and durability characteristics. Fine SCMs such as silica fume and metakaolin can significantly refine the pore structure, whereas slag and fly ash can provide substantial reductions in clinker content and environmental impact. Recent studies indicate that optimized binary and ternary SCM systems can achieve a favorable balance between strength, durability, and carbon reduction. However, excessive replacement levels may negatively influence early-age strength, workability, and carbonation resistance. Therefore, sustainable HPC should be designed through performance-based optimization rather than maximizing SCM content. The article proposes an integrated framework for selecting SCMs and optimizing concrete mixtures according to mechanical, durability, and environmental criteria.

**Keywords:** sustainable concrete; high-performance concrete; supplementary cementitious materials; fly ash; GGBFS; silica fume; durability; compressive strength; embodied carbon; low-carbon construction.

### Introduction

Concrete is one of the most extensively used construction materials worldwide because of its availability, versatility, relatively low cost, and ability to provide high compressive strength. Modern infrastructure—including buildings, bridges, tunnels, industrial facilities, transportation structures, and hydraulic infrastructure—depends heavily on cement-based materials. However, the environmental burden associated with Portland cement production has become an important challenge for the construction industry.

Portland cement is the principal binder in conventional concrete and is responsible for a substantial proportion of the material's embodied carbon. Cement manufacturing involves

energy-intensive processes and the calcination of limestone, during which carbon dioxide is released. Consequently, reducing clinker consumption has become one of the principal strategies for lowering the environmental impact of concrete. Previous research has established that replacing part of Portland cement with SCMs can reduce embodied carbon while maintaining the required engineering performance.

At the same time, the demand for high-performance concrete continues to increase. HPC is characterized by enhanced strength, reduced permeability, improved durability, and carefully controlled fresh and hardened properties. Nevertheless, conventional HPC mixtures frequently contain relatively high quantities of Portland cement and fine reactive powders. This creates a sustainability paradox: a material designed for long service life may initially have a relatively high environmental footprint.

SCMs offer a potential solution to this problem. Common SCMs include fly ash, GGBFS, silica fume, metakaolin, limestone-based materials, rice husk ash, and other pozzolanic or latent hydraulic materials. Their incorporation can modify cement hydration, pore structure, strength development, permeability, shrinkage, and resistance to aggressive environments.

Recent research has increasingly moved beyond the simple replacement of cement toward hybrid or ternary and quaternary binder systems. A 2025 review reported that combinations of SCMs, fillers, industrial by-products, and fibers can simultaneously improve mechanical performance, durability, and sustainability. Some optimized systems have achieved very high compressive strength while reducing life-cycle environmental impacts.

Recent 2026 research also demonstrates the importance of multi-objective optimization. For example, investigations of binary and ternary slag/fly-ash concrete systems have reported substantial carbon reductions while maintaining a balanced combination of strength and durability. Similarly, recent experimental optimization research has evaluated silica fume and slag simultaneously according to compressive strength, corrosion resistance, carbonation, CO<sub>2</sub> emissions, energy consumption, and cost.

Therefore, the objective of this article is to develop a scientifically grounded framework for sustainable HPC based on SCMs and to evaluate the relationship among three major performance dimensions:

1. mechanical strength;
2. durability and service-life performance;
3. environmental sustainability.

The central hypothesis is that **optimized SCM combinations can reduce the environmental impact of HPC without compromising its structural and durability requirements.**

### **Materials and methods**

This study employed a literature-based analytical methodology to evaluate the potential of supplementary cementitious materials (SCMs) for developing sustainable high-performance concrete (HPC). Scientific publications addressing sustainable concrete, high-performance concrete, fly ash, ground granulated blast-furnace slag (GGBFS), silica fume, metakaolin, durability, mechanical properties, and environmental performance were reviewed and synthesized. The assessment was structured around three principal performance criteria: mechanical strength, durability, and environmental sustainability.

The principal SCMs considered in the analysis were fly ash, GGBFS, silica fume, metakaolin, and other mineral or agricultural by-product materials. These materials differ considerably in chemical composition, particle size, mineralogy, reactivity, and hydraulic or pozzolanic behavior. Fly ash generally contributes to improved workability and later-age strength, while GGBFS can provide a favorable combination of strength development and durability. Silica fume, owing to its extremely fine particles and high pozzolanic activity, is particularly effective in reducing pore connectivity and increasing matrix density. Metakaolin can similarly contribute to strength development and pore refinement when appropriately processed and proportioned.

**Table 1. Principal SCMs and their expected contribution to sustainable HPC**

| SCM                             | Main characteristics                        | Principal performance contribution           | Sustainability contribution                                    |
|---------------------------------|---------------------------------------------|----------------------------------------------|----------------------------------------------------------------|
| Fly ash                         | Fine spherical particles; pozzolanic        | Improved later-age strength and workability  | Reduces clinker consumption and utilizes industrial by-product |
| GGBFS                           | Latent hydraulic material                   | Strength development and durability          | Reduces Portland clinker requirement                           |
| Silica fume                     | Extremely fine, highly reactive             | Pore refinement and high early/late strength | Enables high performance with reduced permeability             |
| Metakaolin                      | Highly reactive calcined clay               | Strength and pore refinement                 | Can reduce clinker demand when appropriately sourced           |
| Rice husk ash                   | High silica content when properly processed | Pozzolanic activity and pore refinement      | Converts agricultural residue into useful material             |
| Limestone/calcined clay systems | Complementary physical and chemical effects | Strength and durability optimization         | Potential for substantial clinker reduction                    |

The beneficial action of SCMs is primarily associated with physical filler effects and chemical reactions within the cementitious matrix. Reactive silica and alumina present in many SCMs react with calcium hydroxide generated during cement hydration, producing additional calcium-silicate-hydrate (C-S-H) and calcium-alumino-silicate-hydrate phases. These reaction products contribute to pore refinement, improve the interfacial transition zone, and increase the density of the hardened cement paste. Consequently, appropriately selected SCMs can simultaneously influence strength, permeability, and resistance to aggressive environmental conditions.

The conceptual concrete mixtures considered in the study included a conventional Portland-cement control mixture and alternative mixtures containing individual or combined

SCMs. The proposed systems included fly ash, GGBFS, silica fume, binary combinations of fly ash and GGBFS, GGBFS and silica fume, and ternary combinations of fly ash, GGBFS, and silica fume. The replacement levels were treated as design scenarios rather than experimental measurements and would require laboratory validation before practical application.

The principal mixture-design parameters considered were the water-to-binder ratio, total binder content, SCM replacement level, aggregate grading, superplasticizer dosage, curing conditions, and SCM fineness. Particular attention was given to maintaining a low water-to-binder ratio while ensuring sufficient workability. The assessment framework considered compressive and flexural strength, permeability, chloride resistance, carbonation, shrinkage, and environmental impact. Embodied carbon was evaluated conceptually using the mass of each constituent and its corresponding emission factor. The general environmental impact of a concrete mixture was expressed as:

$$[EC_{\text{concrete}}] = \sum_{i=1}^n m_i \times EF_i$$

where ( $m_i$ ) represents the mass of constituent ( $i$ ), and ( $EF_i$ ) represents its corresponding emission factor.

The percentage reduction in embodied carbon compared with conventional concrete was calculated using:

$$[CO_{2,\text{reduction}}(\%)] = \frac{EC_{\text{reference}} - EC_{\text{SCM}}}{EC_{\text{reference}}} \times 100$$

This methodological framework allows the effects of SCM incorporation to be considered simultaneously rather than evaluating strength, durability, and environmental performance independently.

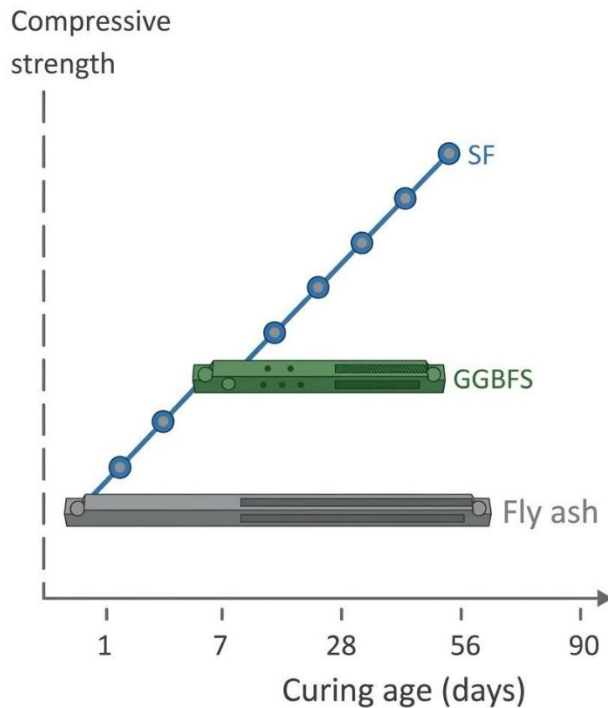
**Table 2. Conceptual HPC mixture groups for comparative evaluation**

| <i>Mix</i>     | <i>Portland cement</i> | <i>SCM system</i>                    | <i>Intended purpose</i>                |
|----------------|------------------------|--------------------------------------|----------------------------------------|
| <i>Control</i> | <i>100%</i>            | <i>None</i>                          | <i>Reference mixture</i>               |
| <i>M1</i>      | <i>70–80%</i>          | <i>Fly ash</i>                       | <i>Lower-carbon concrete</i>           |
| <i>M2</i>      | <i>65–75%</i>          | <i>GGBFS</i>                         | <i>Strength and durability</i>         |
| <i>M3</i>      | <i>80–90%</i>          | <i>Silica fume</i>                   | <i>High-performance matrix</i>         |
| <i>M4</i>      | <i>60–70%</i>          | <i>Fly ash + GGBFS</i>               | <i>Balanced sustainability</i>         |
| <i>M5</i>      | <i>65–75%</i>          | <i>GGBFS + silica fume</i>           | <i>High-performance ternary system</i> |
| <i>M6</i>      | <i>60–70%</i>          | <i>Fly ash + GGBFS + silica fume</i> | <i>Multi-objective optimization</i>    |

## Results

The literature-based analysis demonstrates that the incorporation of SCMs can significantly modify the mechanical, durability, and environmental performance of high-performance concrete. However, the magnitude and direction of these effects depend strongly on SCM type, replacement level, particle characteristics, water-to-binder ratio, curing conditions, and interactions among binder components.

**Figure 1. Conceptual effect of SCM type on compressive-strength development**



From a mechanical-performance perspective, silica fume and metakaolin generally provide strong matrix-densification effects because of their high fineness and reactivity. Fly ash and GGBFS may produce slower early-age strength development in some mixtures but can contribute significantly to later-age strength through continued pozzolanic and hydraulic reactions. The resulting strength development therefore depends on both the type and proportion of SCM used. Literature indicates that appropriately optimized SCM systems can maintain high compressive strength while reducing Portland cement consumption. Binary and ternary SCM systems can be particularly effective because one material may compensate for limitations associated with another.

SCMs can also influence tensile and flexural performance through modification of the cement paste and interfacial transition zone. The formation of additional hydration products can increase matrix density and improve aggregate-paste bonding. Silica fume is particularly effective in strengthening the interfacial transition zone, while the combination of SCMs with fibers can provide additional crack-control and toughness benefits. Nevertheless, tensile and flexural behavior depends on multiple factors, including aggregate properties, fiber characteristics, curing conditions, and mixture proportions.

The durability results demonstrate that SCM incorporation can substantially reduce concrete permeability and improve resistance to several aggressive exposure conditions. Secondary hydration and pore refinement decrease connected porosity and restrict the movement of water and aggressive ions through the concrete matrix. These effects are

particularly relevant to chloride penetration, which is one of the major causes of reinforcement corrosion in reinforced concrete structures. GGBFS and silica-fume-containing systems can provide substantial improvements in chloride resistance when appropriately proportioned and cured.

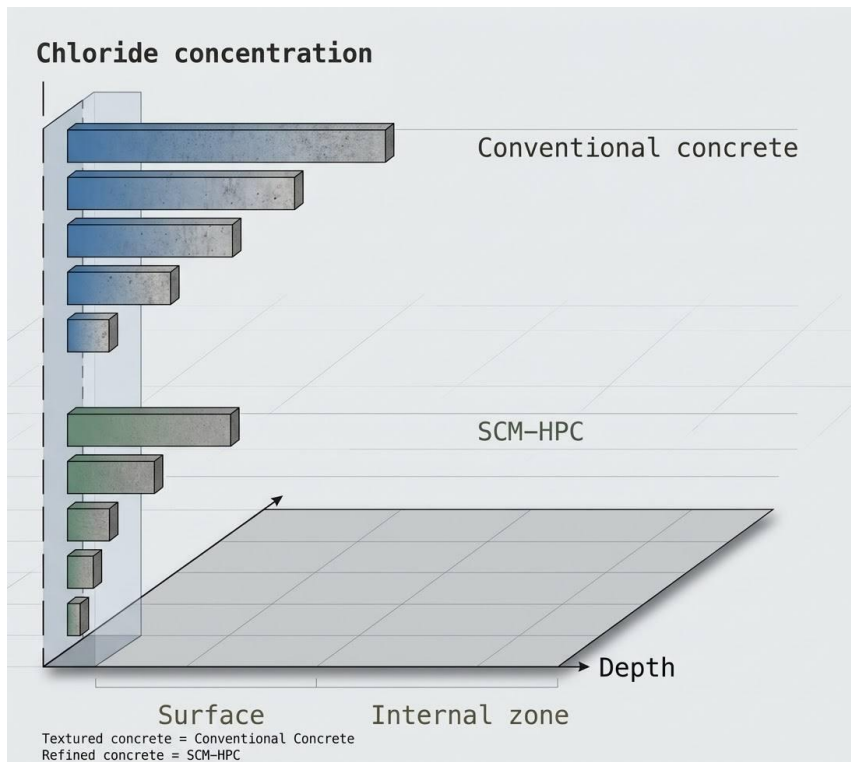
The effect of SCMs on carbonation requires more careful consideration. Although reduced permeability can provide durability advantages, high replacement levels may reduce the quantity of Portland-cement hydration products available to buffer carbonation. Consequently, increasing SCM content does not automatically improve all durability characteristics. Sustainable HPC should therefore be evaluated according to its intended exposure environment, with chloride resistance, carbonation, sulfate attack, freeze-thaw resistance, and corrosion risk considered where applicable.

The environmental assessment demonstrates that SCMs can reduce the embodied carbon of concrete primarily by replacing a portion of Portland cement. Since clinker production is responsible for a substantial share of cement-related emissions, reducing clinker demand can directly reduce the environmental impact of concrete. The magnitude of the reduction depends on the SCM's production and processing requirements, transportation distance, source, and allocation of environmental burdens. Locally available industrial and agricultural by-products may therefore provide particularly attractive sustainability opportunities.

The literature further indicates that binary and ternary SCM systems can achieve a more favorable balance between mechanical performance, durability, and environmental impact than systems relying on a single SCM. For example, combinations of fly ash and silica fume can potentially combine the sustainability and workability advantages of fly ash with the pore-refining properties of silica fume. GGBFS combined with silica fume can similarly provide a dense, durable cementitious matrix while reducing Portland cement consumption. Ternary systems containing fly ash, GGBFS, and silica fume provide additional opportunities for optimizing different performance requirements.

Overall, the results indicate that sustainable HPC should be developed through a multi-objective optimization approach. Maximizing SCM content is not necessarily the optimal strategy because excessive replacement may negatively affect early-age strength, workability, setting characteristics, or carbonation resistance. Instead, the optimum mixture should achieve the required structural strength and durability while minimizing embodied carbon, resource consumption, and, where possible, cost. This performance-based approach provides a more reliable pathway for developing durable and environmentally responsible high-performance concrete for modern construction.

***Figure 2. Conceptual chloride-penetration comparison***



### Discussion

The literature demonstrates that SCMs represent one of the most practical approaches to reducing the environmental impact of cement-based construction while preserving high-performance characteristics.

However, the relationship between SCM content and concrete performance is nonlinear. Increasing the replacement level does not automatically produce a better concrete. At moderate levels, SCMs can refine pore structure, enhance later-age strength, and reduce permeability. At excessive levels, however, early-age strength, setting behavior, workability, and carbonation resistance may become problematic.

This observation is particularly relevant to high-performance concrete. HPC typically uses low water-to-binder ratios and chemical admixtures. The addition of very fine SCMs may increase water demand and influence rheological behavior. Therefore, superplasticizer dosage and particle packing must be optimized together with SCM content.

Silica fume is particularly useful where very low permeability and high strength are required. Its very fine particles can fill voids between cement grains and participate in pozzolanic reactions. However, its high surface area may increase water demand and shrinkage if the mixture is not appropriately proportioned.

Fly ash offers substantial sustainability benefits and can improve later-age performance and workability. Its major limitation is often slower early-age strength development, particularly under unfavorable curing conditions.

GGBFS provides an attractive balance between mechanical and durability performance. Its use can substantially reduce Portland cement consumption while contributing to long-term strength and resistance to aggressive environments.

Ternary systems can provide greater flexibility because one SCM can compensate for the limitations of another. For example, a combination of fly ash and silica fume can combine the

sustainability and workability benefits of fly ash with the pore-refining effect of silica fume. Similarly, slag combined with silica fume can provide high durability while reducing the amount of Portland cement.

Recent research supports this direction. Hybrid SCM systems are increasingly being investigated because the interaction among different mineral additions can provide synergistic improvements in mechanical behavior, durability, and environmental performance.

At the same time, the literature highlights several unresolved issues. SCM quality can vary considerably between sources. Fly ash chemistry, slag fineness, silica-fume characteristics, and calcined-clay reactivity can differ substantially. Therefore, performance-based qualification of SCMs is essential.

Another important issue is the difference between laboratory and field performance. Concrete produced under controlled laboratory curing conditions may perform differently under real construction conditions. Recent reviews therefore emphasize the need for pilot-scale validation and performance-based qualification before widespread implementation of high-volume SCM concrete.

The sustainability assessment should also move beyond cradle-to-gate carbon emissions. A concrete with slightly higher initial embodied carbon but substantially longer service life may produce a lower life-cycle impact than a lower-carbon concrete requiring frequent repair.

This principle is particularly important for HPC because durability is one of its major advantages. The environmental assessment should therefore consider:

**initial material impact + construction impact + maintenance + repair + service life + end-of-life**

rather than only the initial CO<sub>2</sub> emissions.

### **Conclusion**

The development of sustainable high-performance concrete using supplementary cementitious materials represents an important pathway toward reducing the environmental impact of the construction sector without sacrificing engineering performance.

The literature reviewed in this study demonstrates several important conclusions.

First, SCMs can significantly reduce Portland cement consumption and consequently lower the embodied carbon of concrete. Fly ash, GGBFS, silica fume, metakaolin, and other SCMs provide different combinations of chemical and physical effects.

Second, SCMs can improve the microstructure of concrete through secondary hydration and pore refinement. This can contribute to improved later-age strength, reduced permeability, and enhanced resistance to chloride ingress and other aggressive environments.

Third, the effect of SCMs depends strongly on replacement level and material characteristics. Excessive replacement can lead to lower early-age strength, altered workability, and increased carbonation susceptibility in some systems.

Fourth, ternary and hybrid SCM systems offer considerable potential because they can combine the advantages of different materials. Recent studies show that optimized systems containing combinations such as slag, fly ash, and silica fume can provide a strong balance between mechanical performance, durability, and carbon reduction.

Fifth, sustainability should be evaluated through a multi-objective framework. The optimum mixture should not simply minimize cement content; it should satisfy structural

strength, durability, service-life, environmental, economic, and construction requirements simultaneously.

The principal conclusion can therefore be expressed as follows:

**Sustainable high-performance concrete should be designed not as concrete containing the maximum possible quantity of SCMs, but as a performance-optimized cementitious system in which SCM type, replacement level, particle packing, curing, durability, service life, and environmental impact are considered simultaneously.**

Future research should focus on locally available SCMs, ternary and quaternary binder systems, life-cycle assessment, artificial-intelligence-assisted mixture optimization, and long-term field validation. Such approaches can contribute to the development of durable, resource-efficient, and low-carbon construction materials suitable for the next generation of infrastructure.

### References:

1. Samad, S., & Shah, A. (2017). Role of binary cement including Supplementary Cementitious Material (SCM), in production of environmentally sustainable concrete: A critical review. *International Journal of Sustainable Built Environment*, 6(2), 663–674.
2. Park, S., Wu, S., Liu, Z., & Pyo, S. (2021). The Role of Supplementary Cementitious Materials (SCMs) in Ultra High Performance Concrete (UHPC): A Review. *Materials*, 14(6), 1472.
3. Liu, J., Hossain, M. U., Xuan, D., Ali, H. A., Ng, S. T., & Ye, H. (2023). Mechanical and durability performance of sustainable concretes containing conventional and emerging supplementary cementitious materials. *Case Studies in Chemical and Environmental Engineering*.
4. Perera, M. A. G. P., & Ranjith, P. G. (2024). Eco-friendly cementitious composites for enhanced strength: Emerging trends and innovations. *Journal of Cleaner Production*.
5. Moolchandani, K., Sharma, A., & Dharavath, K. (2025). Hybrid use of supplementary cementitious materials, industrial byproducts, and fillers for sustainable high-performance concrete. *Discover Civil Engineering*, 2, 212.
6. Alotaibi, E., Nassif, N., & Alhalabi, M. (2026). Ultra-high-performance concrete for Sustainable Development Goals: A systematic review and conceptual framework. *Journal of Building Engineering*, 123, 115802.
7. Azarhomayun, F., Wei, J., & Khayat, K. H. (2026). Low-carbon concrete for sustainable construction: A comprehensive review of performance characteristics, implementation challenges, and decarbonization pathways. *Journal of Building Engineering*, 128, 116731.
8. Zhao, X., Xie, J., Dai, Q., & Mensah, C. (2026). Performance and carbon reduction of binary and ternary concrete systems with slag cement and fly ash. *Journal of Building Engineering*, 130, 117087.
9. Mahmood, S. M., & Ali, Y. M. (2026). A Systematic Review on the Mechanical and Environmental Performance of Concrete with Supplementary Cementitious Materials. *International Innovations Journal of Applied Science*, 3(1).