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Decarbonizing concrete: A comprehensive review of fly ash and silica fume for low-carbon, durable, and sustainable cementitious systems

Ritu Sharma

Department of Civil Engineering, Swami Vivekanand Subharti University, Meerut (UP), India

Mayankeshwar Singh

Department of Civil Engineering, Swami Vivekanand Subharti University, Meerut (UP), India

Mukesh Ruhela ✉

Department of Environmental Engineering, Swami Vivekanand Subharti University, Meerut (UP), India

Rakesh Bhutiani

Department of Zoology and Environmental Science, Gurukula Kangri (DTBU) Haridwar

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ABSTRACT

The construction industry has an imminent obligation to adapt to climate change and work to diminish carbon emissions through innovative sources and alternatives to traditional Portland cement. Between numerous alternatives, construction materials like fly ash (FA) and silica fume (SF) work as supplementary cementitious materials (SCMs). FA and SF construction materials are a viable alternative considering their potential environmental impact and construction performance. The present study analyzes literature published from peer-review journals from 2000 and a projected 2025 to understand the performance of FA and SF in the construction of low carbon and durable concrete systems. From the synthesis of various studies, it has been found that substituting FA and SF as partial cement replacements leads to a large reduction of CO_2 emissions that are a direct result of the reduction of clinker production and an increase in the strength and durability of concrete. It has also been found that up to 15-30% FA as a partial cement substitute improves long-term strength as well as improves workability of concrete which is due to the spheroidal shape of the particles and the slow pozzolanic reaction. In addition, up to 10-20% of SF as a partial cement replacement will increase the early ages strength of concrete and reduce the permeability of concrete due to the smaller sizes of the SF particles and the rich silica content. It is also found that the use of both SF and FA improves the long-term durability of concrete structures and reduces the intent of chloride and sulphate ions. SF and FA further control the density of the cement and reduces permeability as well as the intent of ailed ions. Besides the technical benefits, the use of these industrial by-products also fosters waste valorization and the construction of resource-efficient buildings. Broadly, the review outlines the synergistic potential of FA and SF along with their positive impact on developing sustainable, high-performance concrete, and highlights the potential of these materials in the construction of resilient, low-carbon infrastructure systems.

Introduction

Growing issues related to climate change and global warming stem from increased concentrations of carbon dioxide in the atmosphere (Mikhaylov and Moiseev, 2020; Yoro and Daramola, 2020). With regards to the construction sector and other industries, it has been revealed that construction is one of the key sectors that has increased greenhouse gas emissions and environmental degradation (Erdogan, 2021; Hu *et al.*, 2022). The last few decades have witnessed increased urbanization and infrastructure development creating a greater need for construction materials. Among various construction materials used, concrete is the most preferred construction material all over the world due to its composite nature, superior mechanical performance, durability and cost-effectiveness.

The environmental impact of concrete should be understood in its entire lifecycle, production, and usage phase, despite its many benefits. Concrete requires copious amounts of naturally occurring aggregates and cement, and cement's production is the single greatest contributor to the lifecycle carbon emissions of concrete. Roughly 1 ton of Portland cement is produced for every 1 ton of CO_2 released in its production (Meyer, 2009). Concrete placement (which requires cement, a component of concrete) and curing accounts for 4.1 billion tons of cement produced every year globally, as sustained from 2015 to 2022 (GCA, 2024; CEMBUREAU, 2024). Alongside the aviation industry, cement is 7-8% of the world's man made CO_2 emissions. Consequently, finding alternative cementitious materials and reduc-

Corresponding author E-mail: mruhela@gmail.com
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ing the amount of cement in concrete is of utmost urgency and necessity.

As a response to emerging challenges related to the environment, a vast amount of research has focused on the use of supplementary cementitious materials (SCMs) within concrete. The use of industrial by-products such as fly ash (FA) and silica fume (SF) has been studied extensively due to the associated pozzolanic activity and the positive impact on the environment. Fly ash, a product of the combustion of coal in thermal power plants, contains a significant amount of reactive silica and reactive alumina. Likewise, silica fume is a by-product of the production of silicon and ferrosilicon alloys. Reactive silica and alumina are known to contribute to secondary hydration reactions in cementitious systems.

It has been shown that the partial replacement of cement with FA and/or SF increases the mechanical properties and durability of concrete while significantly decreasing clinker consumption and the associated carbon footprint of cement production (Siddique, 2004, Zhang, and Li, 2013). The materials studied have also been shown to improve the long-term strength of concrete, to micro-structure the pore and to increase the resistance of concrete to the deteriorating effects of chemicals. There still exists several gaps in knowledge related to this topic. These include optimal levels of SCM replacement, FA-Silica fume (SF) combinations and the effects on the mechanical and durability characteristics of concrete in different environments.

For this reason, present review will try to explore the current state of research on FA and SF as sustainable cement alternatives in concrete, analyzing literature of synthesis for the FA and SF influence on the performance criteria of compressive strength, flexural strength, workability, and durability. Considering the above, the review will also determine the best replacement ratios in addition to evaluating the freedoms and constrains of each and their practical considerations for field use. Present study will integrate the results of research data and field data to strengthen the understanding of sustainable concrete. The review will focus on the academic/engineering interface of sustainable concrete and the combined stresses of recycling, valorization, and both positive and negative use of industrial by-products in concrete.

Materials and methods

The study uses systematic review methods for assessing the applicability of FA and SF as supplementary cementitious materials for construction of sustainable concrete. Relevant published scientific studies were retrieved from major scientific databases including Scopus and Google Scholar, for the period of January 2000 to July 2025. The keywords used were “fly ash,” “silica fume,” “supplementary cementitious materials,” “durability,” and “sustainable concrete.”

To keep the literature review transparent and organized, a method inspired by PRISMA was adopted. The first step was the removal of duplicate entries, followed by screenings based on title and abstract. Full texts were then assessed for eligibility based on the preset inclusion criteria. Only peer-reviewed articles that contained quantitative experimental findings on the partial cement replacement of FA and/or SF were included. The articles that lacked pertinent technical information or were not related to the performance of concrete were excluded from the review.

For each study eligible for collection, key data points such as mixing ratios, the levels of FA and SF substitution, curing conditions, and performance metrics were collected and examined systematically. The parameters collected consisted of compressive, tensile, and flexural strengths, permeability and durability, and the measured potential CO_2 emissions reductions. The synthesis of data collected aimed to reveal the performance and sustainability trends at different levels of FA and SF substitution in eco-efficient concrete systems.

The entire process of identification, screening, eligibility, and inclusion in this systematic review is represented in Figure 1.

Industrial by-products in concrete

Using industrial by-products in concrete can improve the performance of concrete and decrease its negative environmental effects. In particular, the effectiveness of FA and SF as supplementary cementitious materials that substitute a portion of the Portland cement in concrete mixtures, in addition to their positive impact on the mechanical properties, assists in the addition of the microstructure of the cementitious matrix.

Both FA and SF include reactive forms of silica and alumina which undergo secondary pozzolanic reactions with the calcium hydroxide produced during cement hydration, resulting in the formation of additional cementitious calcium-silicate-hydrate (C–S –H) gel, which improves the strength of the cement matrix and reduces the connectivity of pores. Consequently, concrete with these SCMs demonstrates improved strength, durability, and sufficiency while generating a lower heat of hydration. The utilization of these industrial by-products fosters a circular economy and sustainable construction practices, as they divert waste from landfills and reduce the demand for virgin resources. Fly ash is a by-product of the combustion of coal at thermal power stations (Ishak, Shapie, and Lai, 2020). The by-product primarily consists of glassy spherical particles that, in fresh concrete, improve workability and decrease the amount of water needed due to the “ball-bearing effect.” Chemically, FA is a highly pozzolanic material due to the presence of Silica (SiO_2), Alumina (Al_2O_3), and Iron Oxide (Fe_2O_3) in significant amounts.

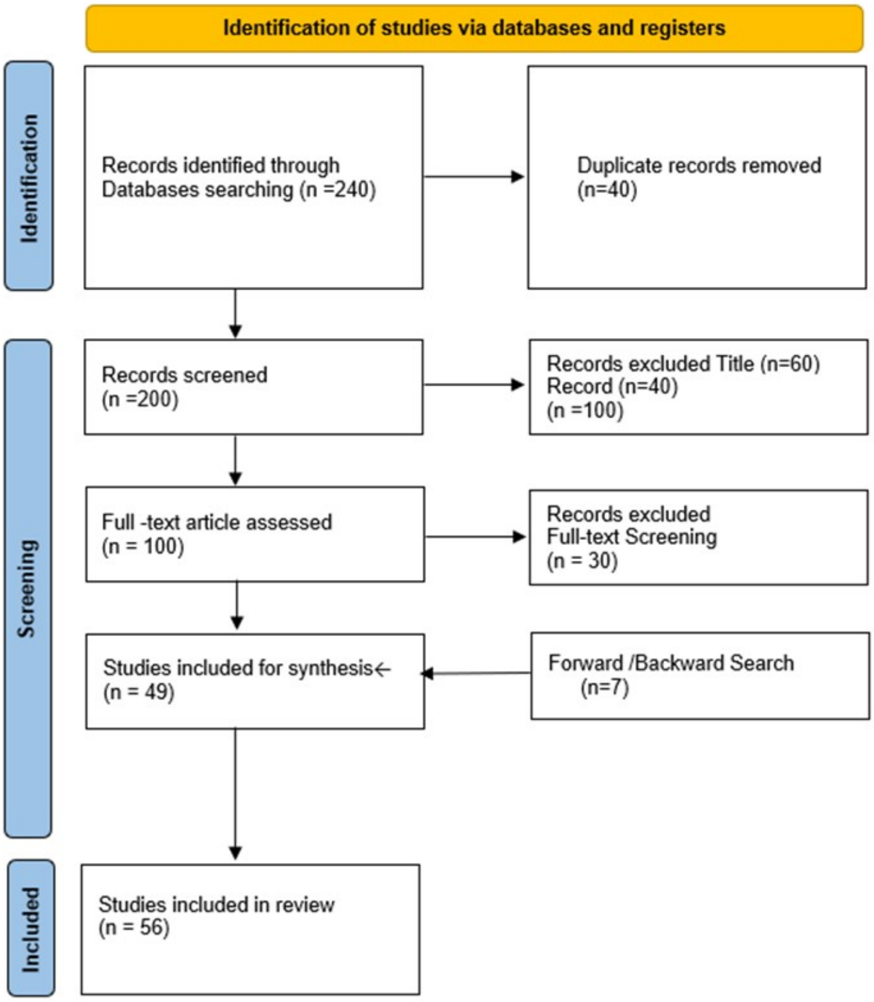

Figure 1: PRISMA flow diagram illustrating the study selection process

The incorporation of fly ash (FA) into concrete allows FA to engage with calcium hydroxide ($Ca(OH)_2$) through a secondary hydration reaction to create more calcium silicate hydrate (C–S–H) gel. This reaction results in a gradual increase in microstructural density (Siddique, 2004; Sereewatthanawut *et al*., 2023). Although the rate of increase of microstructural density is directly correlated to the age of the concrete being used, this reaction does, in general, increase the long-term strength and durability of the structure. This process, called a pozzolanic reaction, occurs at a significantly lower rate compared to the rate of cement hydration. Therefore, fly ash-based concrete tends to have better workability, longer setting time, and greater strength increase at older curing ages (Siddique, 2004; Yazıcı, 2008). These traits provide fly ash with the ability to be a valuable supplementary cementitious material (SCM) for decreasing clinker usage and, with that, decreasing CO_2 emissions and increasing the durability of the concrete (Shaikh, Supit, and Sarker, 2014).

Silica fume

Silanol silicate fume (SF) is a highly fine and ultrafine powder that is a by-product of the manufacture of silicon and ferrosilicon alloys. As a result of SFs extremely fine particle size and its high percentage of amorphous silica, it is, on average, 100 times smaller than the average cement particle size. These properties of SF lead to a greater degree of highly reactive pozzolanic behavior than most materials used in cementitious systems.

Once SF is combined with concrete it has the ability to produce more C-S-H gel during the cement hydration process as it reacts with the calcium hydroxide produced during that process. SF has the ability to micro-fill. This allows it to enhance the packing density and diminish the spaces present between pores. SF in concrete diminishes the spaces present between the pores to improve the Interfacial Transition Zone ITZ with the aggregates and cement paste. This results in the concrete being more durable and stronger.

Concrete, in general, has lost moisture, and diminished permeability. It has proven to enhance the chloride, sulfate, and moisture ingress attacks. It has shown that when the replacement SF ratio is

Table 1: Elemental composition of industrial waste-derived materials

Waste Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI	Ref
FLY ASH	51.8	26.4	13.2	1.61	1.17	0.21	0.31	0.68	0.5	(Shaikh, Supit and Sarker, 2014)
	46	17.8	18.2	8.4	0.95	2.59	0.59	2.16	1.49	(Kawashima *et al.*, 2013)
	42.14	19.38	4.64	26.96	1.78	2.43	…	1.13	1.34	(Yazıcı, 2008)
	49.61	18.49	10.55	9.57	5.7	…	2.58	2.52	…	(Shaikh, Supit and Sarker, 2014)
	51.8	26.5	8.5	4.81	1.1	0.6	0.67	3.27	1.47	(Mustapha *et al.*, 2021)
	54.56	21.7	8.85	4.45	1.48	0.59	1.03	3.85	…	(Ma *et al.*, 2022)
SILICA FUMES	92.5	0.72	0.96	0.48	1.78	…	0.5	0.84	1.55	(Chalah *et al.*, 2022)
	93.83	1.174	0.711	1.777	0.222	0.141	0.301	0.309	1.95	(Xiong *et al.*, 2022)
	91	0.4	1.8	1	0.9	0.18	…	1.7	….	(Zheng *et al.*, 2022)
	93.6	1.3	0.9	0.5	1	<0.10	0.36	0.9	1.88	(Nili, Ramezanianpour and Sobhani, 2021)
	96.57	0.06	0.06	0.51	0.25	0.12	0.16	0.73	1.41	(Wetzel and Middendorf, 2019)
	95.58	0.71	0.81	0.9	0.6	…	0.17	0.32	…	(Choudhary *et al.*, 2020)
	94.8	0.6	0.3	0.27	0.5	0.05	0.3	0.8	1.9	(Shah and Scott, 2022)
	96.755	0.279	0.247	0.194	0.343	1.289	…	1.289	2.61	(Xi *et al.*, 2022)
	93.34	0.62	1.75	0.99	0.58	…	0.68	1.89	….	(F. Wang *et al.*, 2022)
	92.26	0.89	1.97	0.49	0.96	0.33	0.42	1.31	….	(Yazıcı, 2008)
	94.85	0.22	0.18	0.32	0.37	0.79	0.22	0.64	0.64	(Lv *et al.*, 2022)

Table 2: Distinct characteristics of fly ash and silica fume in concrete behavior

Property	Fly Ash (FA)	Silica Fume (SF)	Reference
Pozzolanic Activity	Moderate; slower reaction with $Ca(OH)_2$ leading to long-term strength gain	Very high; rapid reaction due to ultrafine, amorphous SiO_2	(Siddique, 2004; Xu *et al.*, 2016)
Effect on Workability	Improves flow because of spherical “ball-bearing” effect	Reduces workability; higher water demand	(Siddique, 2004, 2011)
Setting Time	Often delays setting at higher FA dosages	Generally little change; may slightly accelerate	(Thomas, 2007; Sereewatthanawut *et al.*, 2023)
Sulfate resistance	Improved via reduced CH and permeability	Excellent owing to refined pore structure and low ion ingress	(Thomas, 2007; Shah *et al.*, 2018)
Carbonation resistance	Slightly lower buffering capacity but mitigated by curing	Slightly reduced buffering, but dense matrix slows ingress	(Siddique, 2004; Environment *et al.*, 2018)
CO_2 footprint	Significant reduction through clinker substitution	Also lowers CO_2 emissions in HPC systems	(Andrew, 2019)
Cost / availability	Generally economical and widely available	Costlier; availability limited	(Shamseer *et al.*, 2015)

between 5-10% it will enhance the compressive strength and the durability characteristics.

Concrete performance is elevated with the synergy use of SF and other SCMs. This is even more present with specific FA. FA yields long term strength due to slow pozzolanic reactions, while SF allows the concrete to develop micro-structural strength.

The chemical make-up of FA and SF plays a huge role in their ability to be pozzolanic and their ability to be used as SCMs. FA typically has a high percentage of silica (≈42-55%), with alumina (≈18-27%), and iron oxide (≈8-18%), with a less significant amount of calcium oxide). This puts FA in the Class F range of fly ashes. SF has an even higher percentage of silica (greater than 90%) with very small amounts of other oxides, therefore having a reactive structure that is super amorphous. The low loss-on-ignition (LOI) (less than 1%) present in both materials proves that they have very low amounts of unburnt carbon, which is a sign of consistent reactivi-

ty and improved performance in cementitious systems.
The practical impact of both FA and SF on the properties of concrete are compared in Table 2. Table 2 summarizes the impact of FA and SF on pozzolanic activity, workability, setting time, strength gain, and durability.

Results and Discussion

The use of supplementary cementitious materials like fly ash (FA) and silica fume (SF) as partial replacements of Portland cement affects the fresh and hardened properties of concrete. The materials improve some of the rheological behavior of fresh concrete mixtures and the performance and durability of hardened concrete. FA is known to enhance workability and contribute greater to long term strength of concrete. FA contains greater particle sizes , and when compared to SF, has low pozzolanic reactivity. SF on the other hand, is known to enhance strength of concrete by lowering the permeability. The combination of FA and SF improves the microstructure of the cementitious matrix and improves strength, performance, and durability of concrete creating a more sustainable concrete.
The addition of FA to concrete mixtures improves the workability of concrete. FA particles are known to streamline the workability of concrete, causing up to 30% decrease in water requirement and lowering internal friction of concrete mixtures due to the observed ball-bearing effect (Thomas, 2013).In contrast, SF has a reverse effect on the attributes of fresh concrete, i.e., increased cohesiveness and increased viscosity of the concrete mixture, leading to a decrease in slump values, except when a high-range water-reducing admixture is added (Aïtcin,

Table 3. Summary of selected literature on strength behaviour of concreteincorporating FA and SF at various replacement levels

Ref	Industrial waste source	Replacement proportion	Best performing mix	Significant results
(Tripathi *et al.*, 2020)	SF	SF 5, 10, 15, 20 & 25%	SF 20%	Incorporating SF exhibits improved strength and acid resistance, though it tends to have reduced workability.
(Hamada *et al.*, 2023)	SF	0-20 %	Silica fume 15%	Minor additions of silica fume (SF) can enhance the workability of concrete. Strength gains are observed as SF content rises to 15% and with extended curing durations, but beyond this limit, strength may decrease. SF incorporation up to 15% also enhances durability by minimizing pore structure and water absorption.
(Rehman *et al.*, 2020)	SF	Silica fume 0%, 5, 8, 11, 15%	SF 11%	Rising silica fume content negatively affects the workability of concrete, while mechanical strengths—compressive, tensile, and flexural—show improvement up to 11% SF replacement and then diminish with further addition.
(Akarsh, Marathe and Bhat, 2021)	SF	0%,3%,5%,7%,and10 %	sf 7%	The optimum dosage of 7% SF was found to improve compressive strength by about 29.5%, indicating a significant pozzolanic effect.
(Ali *et al.*, 2021)	SF	0,10%,15%,and20%	SF 20%	A 20% of SF in concrete mix caused a 4% decline in C.S relative to the reference mix.Likewise, higher SF content caused further strength loss due to the pozzolanic reaction..
(Liu *et al.*, 2020)	SF	5%,10%,20%and30%	SF 5%	The C.S of the concrete was raised to 127.5 MPa when 5% SF was incorporated in place of cement. When the SF content was raised to 10%, compressive strength was reduced by 8.4% in relation to the control mix. This suggests that although low SF replacement enhances strength, larger quantities will negatively affect it because the microstructure and workability of the concrete change.
(Oner, Akyuz and Yildiz, 2005)	FA	15, 25, 33, 42, 50, 58% (partial cement replacement)	~40%	The strength improves to an optimal level of about 40%, after which it begins to decline.
(Berryman *et al.*, 2005)	FA	25-75% (Class F), 25-65% (Class C)	25-35% depending on class	7 days compressive strength tests show that about 35% Class C or 25% Class F give highest early strength; substitutions up to 65% (C) or 40% (F) still meet ASTM strength requirements in some cases
(Khan and Shariq, 2019)	FA	25%, 40%	40%	Studied 0%, 25%, 40% A; 40% FA was found to be “optimum level” in terms of replacement with respect to residual strength after heating to 400 °C under certain conditions
(Saha, 2018)	FA	20%, 25%, 30%	20%-30%	Low early strength vs control, but gradual improvement over longer curing (28-180 days). FA mixes show reduced drying shrinkage, lower porosity, lower water sorptivity, and lower chloride permeability.

2000).
Studies have shown that a combined use of FA and SF achieves a unique optimal balance of workability and stability of concrete mixtures. Whereas FA improves flowability, SF binds the mixture together thereby reducing segregation and bleeding. This set of properties of FA + SF concrete blend contributes to significant stability and homogeneity of the concrete mixture and positive rheological properties to the blend (Faraj *et al*., 2021).

Mechanical properties

Numerous studies have documented that an addition of FA and SF in concrete mixes improves the mechanical performance of the resultant concrete. SF has a notable influence on the increase of the early-age strength due to the quick pozzolanic reaction and the quick formation of more C–S–H gel early on in the hydration phase, while FA mainly contributes to the enhancement of strength of the concrete at later stages through sustained pozzolanic reaction and the improved microstructural densification (Nadeem, Jameel, and Ibrahim, 2022; Q. Wang *et al*., 2022).
American Coal ash association (2013), Kawashima *et al*. (2013), and Luo *et al*. (2022) show that for optimum compressive strength, SF replacement levels of 10-20% should be used, while for stable long-term strength development, FA replacement levels of 15-30% should be used, where both strength and stability are required. The combination of both materials simultaneously used produces a synergystic effect and improves compressive, tensile, and flexural strengths, as well as the refinement of the interconnected pore structure and densification of the matrix (Shivastava *et al*. 2014, Shukla *et al*. 2023).

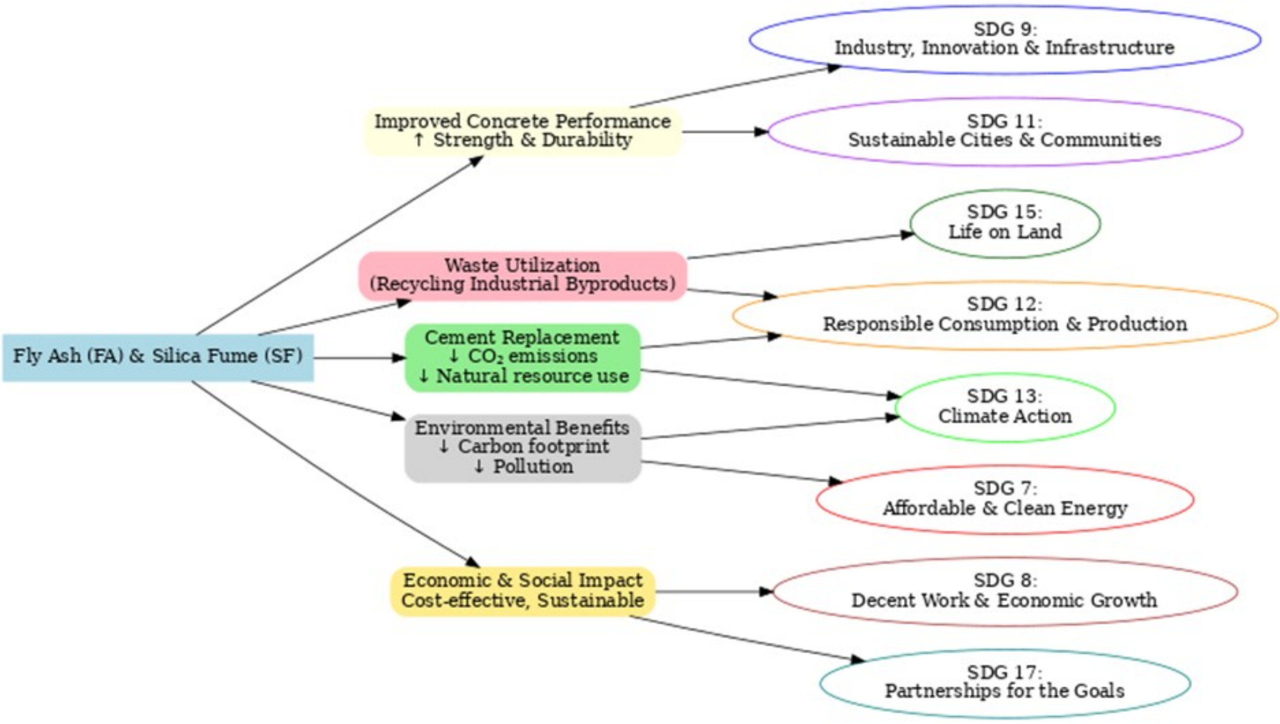

Figure 2:: Sustainability implications of FA and SF utilization in concrete, highlighting contribution towards SDG 9, SDG 11, SDG 12 and SDG 13

The relative values in Table 3 clearly show that for concrete mixes with FA and SF, a greater level of compressive strength is achieved than in the conventional control mixes, which is particularly true after 28 days of curing. This fact coupled with the observed increase in tensile and flexural strengths, clearly indicates a degree of enhancement in adhesion and overall structural integrity of the cementitious matrix (Venkitasamy *et al*. 2024).

Durability performance

The most pronounced advantage regarding FA and SF in concrete is durability. FA reduces free calcium hydroxide in the hydrated matrix and subsequently the alkali-silica reaction and sulfate attacks. SF reduces chloride ion penetration due to its micro-filling effect and pore refinement (Leung *et al*., 2016).
Concrete mixtures with around 10% SF and 30-40% FA have shown to perform significantly better in terms of the corrosion protection of embedded reinforcement and the permeability of concrete (Yazıcı, 2008). These changes are most likely due to the development of a less porous and a more micro-dense matrix.

Sustainability implications

Moreover, the durability and mechanical benefits with the use of FA and SF offer further benefits in terms of sustainability. Workability is enhanced with

the use of FA due to the spherical particle geometry. Also, SF reduces permeability and increases the early age compressive strength. When combined, these constituent parts create a more sustainable concrete and enhance the longevity and decrease the overall maintenance requirements.
The ideal range of performance, workability, and durability is achieved when Fly Ash (FA) replacement levels range from 15% to 30% and Silica Fume (SF) levels range from 10% to 20% (source).
FA and SF positively affect the environment by reducing the amount of clinker needed in cement manufacturing. This decreases both the amount of CO_2 and the energy required in cement production. Furthermore, using these by-products of industrial processes in construction materials diverts waste from landfills, fosters sustainable waste practices, and creates circular economy opportunities in construction. Concrete systems based on FA and SF offer significant environmental benefits and improve structural performance.
The use of these systems in construction aids in the fulfillment of several global sustainable development goals, including the UN SDG 9 (Industry, Innovation and Infrastructure), UN SDG 11 (Sustainable Cities and Communities), UN SDG 12 (Responsible Production and Consumption), and UN SDG 13 (Climate Action) as shown in Table 2.

Note: SF – Silica Fume; CF – Coconut Fiber; FA – Fly Ash; C.S. – Compressive Strength; F.S. – Flexural Strength.

Conclusion

Adopting construction materials that are environmentally sustainable is necessary to achieve international climate change and sustainability objectives. The use of industrial by-products as supplementary cementitious materials has been proven to significantly enhance the sustainability and circular economy of concrete as a construction material.
The analysis reveals that the addition of FA and SF substantiated the concrete's microstructural and mechanical durability and strength. The formulation of a more compact cementitious structure and the improved response to more extreme environmental and aggressive conditions help illustrate the cement's longitudinal support of the structure. The valorization of these industrial by-products (waste) and lessening the dependence on energy demanding clinker (cement) manufacturing cycles underscores the waste to value approach (circular economy) in the construction industry.
The positive effects of FA and SF `co-operation' approach towards early stage strength and later mechanical strength. This `co-operation' approach also illustrates the significant shift from the conventional strength based approach to the more sustainability focused material design (or engineering) approach in modern concrete.
However, research is still needed to address these issues including variability of materials, analysis of constituent materials, variations in methods to assess differences and establish various methods of standardization to measure the consistency of results. This points to the need for research on construction for more durable systems and design to extend the life of a construction to achieve more environmentally durable systems using less industrialized materials.
The addition of cementitious materials from industrial by-products is a logical and workable, and extremely vital (in conjunction with other systems) way to meet the goals of durable, resilient, and low carbon infrastructures and to meet the needs of sustainable construction.

Conflict of interest

The authors declare that they have no conflicts of interest.

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