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Review Article

Enhancing Sustainability and Economics of Concrete Production through Silica Fume: A Systematic Review

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Abstract

This review article addresses the problems associated with the carbon footprint of the cement industry. The PRISMA framework methodology was for data extraction from published studies. In-depth research has been done in the literature on using silica fume as a cement replacement in concrete production, considering environmental, engineering, and economic (EEE) factors. The strength, durability, and economic parameters results revealed a positive variation of up to 5–20% substitution of silica fume. However, most past studies reported the threshold at a 10% replacement ratio. A novel benefit-cost ratio analysis was also done in this review study. The benefit-cost ratio analysis reveals the economically beneficial effects that can be achieved in sustainable silica fume-based concrete with a (5–20%) silica fume combination. The benefit-cost ratio showed positive effects, up to 20% cement replacement with silica fume. Hence, the higher cement replacement with silica fume is also beneficial in terms of the benefit-cost ratio. Further research has been proposed based on the findings of this review study.

Keywords: CO_2 Emission; Silica Fume; Silica Fume-Based Concrete; Benefit-Cost Ratio.

1. Introduction

The handcrafted economy of the past has given way to a mechanized industry today. Another significant change brought on by the Industrial Revolution was that the world's population had crossed one billion at the beginning of the 19th century [1]. According to the United Nations (UN) latest demographic projections, the world population will exceed 9 billion by 2045 DeSA [2]. The World Urbanization Index states that 55% of the population lives in urbanized areas, projected to escalate to 68% by 2050 Bongaarts [3]. Rapid urbanization needs infrastructure, ultimately increasing the demand for construction materials [4–6].

The consequences of rapid economic growth led by the Industrial Revolution have raised CO_2 emissions on a colossal scale [7–10]. CO_2 emissions have increased to 386 ppm, exceeding natural limits since the beginning of the 21st century due to world urbanization [11–14]. The world continues to urbanize and is required to develop infrastructure for its inhabitants. The fundamental construction materials for this development are natural aggregates, river sand, and cement. About 40% of CO_2 emissions in cement kilns are contributed by burning fossil fuels such as coal [15–17]. The UN's 11th Sustainable Development Goal (SDG) has set targets to make cities resilient, inclusive, sustainable, green, and safe by 2030 [7]. Therefore, environmental scientists and climate change committees have set stringent goals to lower CO_2 emissions from all sectors to maintain the temperature below 1.5°C under the Paris Agreement of 2015 [18].

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The construction sector looks forward to more sustainable solutions for replacing OPC in concrete production. It has been discovered that SF is a successful supplementary cementitious material (SCM) that can replace OPC in concrete manufacturing [8, 18–21]. Still, there is a debate on the correct percentage of SF incorporation in the design mix of concrete. The most up-to-date published studies [18, 22–31] in the period 2022–23 reported the strength and durability assessment of silica fume-based concrete. The reported studies show variation in the concrete properties up to a 5-20% replacement of OPC with SF. However, the splitting tensile and flexural strength performed well, with up to 20% replacement of OPC with SF. The increment in durability performance was improved up to a 10% replacement ratio.

Ahmad et al. [32] replaced 10% OPC with SF and observed better concrete strength and durability than the control mix without SF. At 15%, the incorporation of SF improved the splitting tensile and flexural strength by 28%, as studied by Othuman Mydin [33]. A study by Akhtar et al. [24] disclosed that incorporating 20% SF improved strength characteristics. However, at 20%, the increment rate was much lower than the 10% incorporation. Another study by Srivastava et al. [34] compared up to 35% replacement of OPC and found that the OPC replacement with SF in the higher amount was also adequate. The replacement ratio (5–12.5%) significantly improved the strength and durability. New experimental research with higher SF percentages would be a significant step toward reducing the cement industry's carbon footprint.

Extensive research and development have been done to replace the OPC with SCMs, such as silica fume, flyash, and rice husk, to replace the OPC in concrete manufacturing. However, the scope of research is still available to utilize these SCMs in high percentages to avoid excessive usage of OPC. This review article studied silica fume replacement with OPC in concrete manufacturing. A novel review attempt has been discussed on silica fume-based concrete performance from environmental, engineering, and economic (EEE) aspects. It will provide a new direction of unstudied research for prospects and fill the knowledge gap that has not been considered yet.

2. Research Methodology

The PRISMA framework was used in the current study's systematic literature review (SLR) technique. The following four steps were considered for the SLR methodology of this review study.

I. ***Search Technique*:** The search technique is targeted by the databases of the selected keywords "CO_2 emission from the cement sector", "silica fume," and "silica fume-based concrete" were used. The database is extended for all queries through, at present, 2023.

II. ***Search Criteria*:** The PRISMA framework proposed by Moher et al. [35] is used for search criteria. The search primarily focuses on mapping already published literature on silica fume concrete, sustainable materials, carbon footprint, and waste management. The search then focused on SF-based concrete by substituting OPC with silica fume. Articles from other irrelevant sources were excluded. A total of 332 articles were eliminated at this stage.

III. ***Quality Assessment*:** The peer-reviewed articles, published conference proceedings, technical reports, and case studies were included. All records were thoroughly examined for accuracy and quality for this review paper. The abstracts of the scholarly articles were carefully examined and refined to determine the inclusion process. The data selection detail process is presented in Figure 1.

IV. ***Data Extraction*:** The total number of 124 articles were chosen for this review study. The selected paper comes from journal articles, technical reports, technical reviews, and conference proceedings. More than 90% of the papers published between (2015-2023), are in English and cover various topics, including silica fume-based concrete, reduced CO_2 emission from building materials, and eco-friendly sustainable construction materials. Identified records after database searching.

3. Environmental Impact

3.1. Carbon Footprint

During the pre-industrial period, the levels of CO_2 were around 280 ppm, but at the beginning of the 21st century, they rose to 386 ppm. The rising CO_2 concentrations in the atmosphere make it a greenhouse heat-trapping gas. The earth's naturally rising greenhouse effect keeps its temperature at 1.5°C on average, whereas anthropogenic activities incorporate excessive CO_2 into our atmosphere, increasing its natural optimum temperature [36, 37]. A report discussed by the Inter-Governmental Panel on Climate Change (IPCC) in the Paris Climate Agreement states that any rise in global temperature is more than 1.5°C (1.5°C is the pre-industrial temperature). It is intolerable and keeps us at high risk of natural calamities such as frequent cyclones and droughts, resulting in famine and ultimately bringing many diseases.

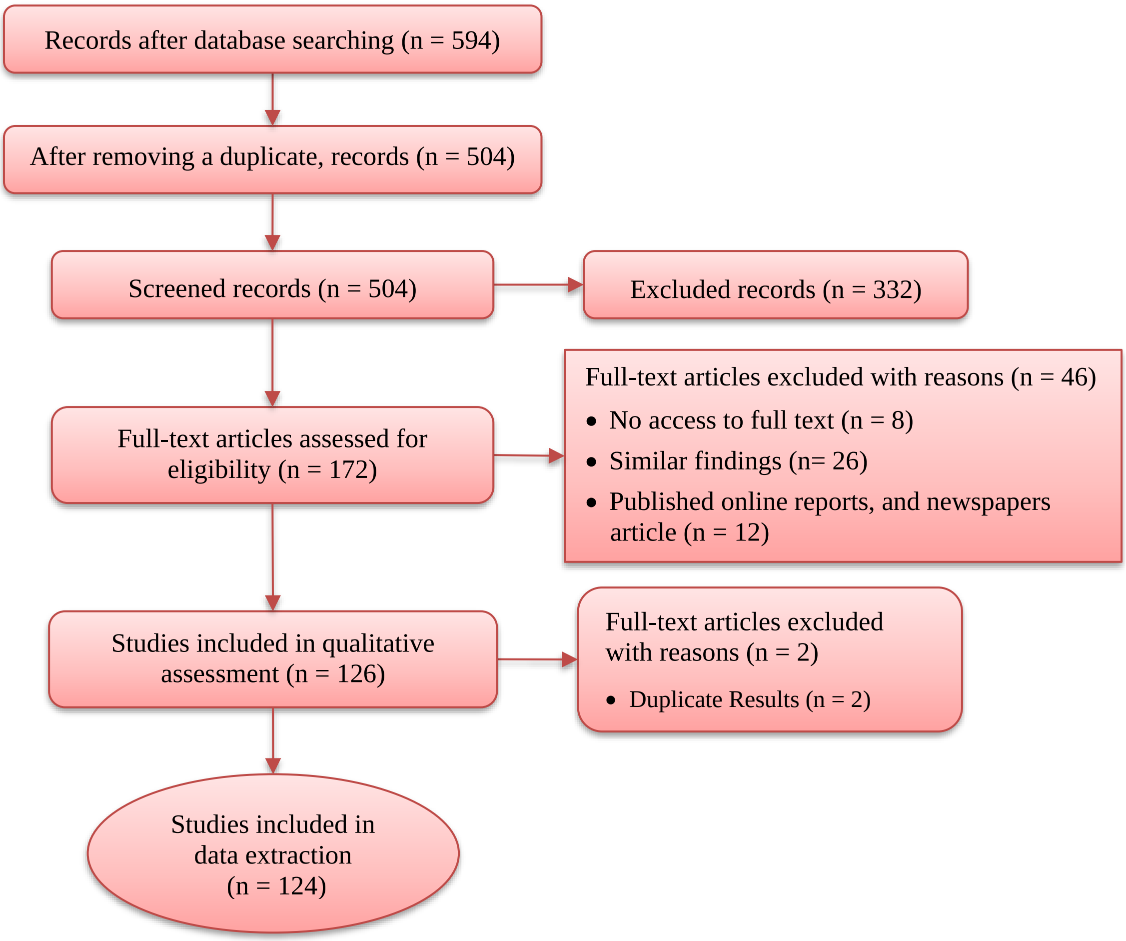

Figure 1. Data extraction methodology

The first conference of parties (COPs) in Rio de Janeiro, Brazil, in 1992, called COP-1, was hosted by the United Nations Framework Convention on Climate Change (UNFCCC). A treaty was signed to cut global emissions of CO_2 by 5% compared to 1990s levels by the end of 2008–2012. The COP-15 held in Copenhagen, Denmark, in 2009 declared that the increase in average global temperature should be less than 2°C. In Doha, Qatar, COP-18 was held in 2012; the deadline was extended to 2020. In Paris, COP-21 was accommodated by France in 2015. One hundred ninety-six countries, almost the entire international community, pledge to maintain the increase in average global temperatures to less than 1.5°C. The COP-23 was held in Bonn, Germany, in 2017, where attempts were made to continue implementing and improving CO_2 reduction promises. The COP-25 took place in Madrid, Spain, in 2019 but ended up leaving a void that will only be filled if policymakers sincerely deal with climate change issues. After reviewing them avidly, the COPs failed to enforce the policies with no positive outcomes. The most recent COP-26 in Glasgow, UK, in 2021, focuses on tangible goals to reduce CO_2 emissions from different sectors [38–40].

3.2. Carbon Footprint from the Cement Industry

The cement sector generated 4.3 gigatons of greenhouse gases globally, making it the top generator among all other industries [37, 41–43]. The CO_2 emitted can be reduced by reusing and recycling SCMs. The cement industry produces 2.4% of CO_2 emissions, on which modern construction depends firmly. When calcium carbonate is heated during calcination, it is described in Equation 1.

$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2\uparrow \quad (1)$$

The IPCC states that Equation 2 can be used to determine the CO_2 emissions from clinker formation during calcination, as shown in Equation 2.

$$\text{Production data} \times \text{CKD correction factors} = CO_2 \text{ emission from clinker} \quad (2)$$

The dust released from the cement kiln during the annual cement production in CKD [44]. Table 1 displays the information on CO_2 emissions gathered by the world scenario [45–50]. The worldwide CO_2 emissions in metric tons are presented in Table 1. China reported the highest CO_2 emissions since 2005, as presented in Table 1. India ranks second in the world for CO_2 emissions, behind China. The calcination process significantly impacts environmental problems in cement factories. According to Mokhtar & Nasooti [51], 50–60% of CO_2 emissions are released during clinker production. Burning fossil fuels like coal is also responsible for high CO_2 emissions from cement kilns [15, 16, 52, 53]. Scientists and concrete designers have suggested a better and more sustainable substitute, SF, to replace OPC. The fineness of SF helps to fill the voids, and a more compact microstructure is formed by using SF in place of OPC, enhancing the concrete's strength and durability [54–58].

Table 1. Worldwide CO_2 emissions data from cement production

Year	AUS	CAN	FRA	GBR	USA	CHN	IND	IDN
2005	3664.127	7599.116	9108.285	5941.163	46194.12	411649	60829	18770
2006	3888.062	7742.186	9165.701	5892.78	46850.74	470087	64252	19303
2007	3971.547	7745.256	9334.063	6117.015	45508.88	514981	68535	19824
2008	3862.908	6983.866	8879.584	5202.562	41415.65	525924	73126	20772
2009	3829.017	5391.039	7679.229	3720.482	29614.64	583560	85141	19650
2010	3548.615	6039.28	7887.542	3792.01	31449.24	639592	91424	19052
2011	3495.532	6057.452	8065.248	4095.726	32208.36	708564	96579	20695
2012	3518.237	6562.168	7501.86	3723.954	35270.35	714782	102028	22675
2013	3294.42	5981.88	7299.551	4029.11	36369.23	748323	104523	24554
2014	3137.567	5945.506	6974.62	4214.814	39439.02	778627	108061	25121
2015	3076.156	6263.215	6606.094	4460.569	39907.29	733679	111766	25121

AUS – Australia, CAN – Canada, FRA – France, GBR – United Kingdom of Great Britain and Northern Ireland, USA – United States of America, CHN – China, IND – India, IDN – Indonesia; Source: (IPCC) sector 2A1 Cement Production.

3.3. Silicon Production and Silica Fume

3.3.1. Silicon Production

Silicon, after oxygen, is the earth's most abundant element. It combines with oxygen to form natural and pure silicon dioxide and silicates. Silicon as an element was recognized in the early 20th century, and its production started at industrial levels. Due to the onset of the IT sector, the demand for calculators, computers, and everyday electronic devices has increased, whose essential component is silicon chips. To produce chips, extremely pure silicon was produced by the metallurgical extraction of ferro-silicate ores and pure quartz [59]. Figure 2 shows the silicon production worldwide in thousands of metric tons. It can be seen from Figure 2 that the USA produced 310 thousand metric tons, and Norway, Brazil, and Russia produced 350, 390, and 580 thousand metric tons, respectively. China produces the world's largest industrial silicon, around 6,000 metric tons annually. China is the largest producer of silicon because most developed nations have outsourced the production and manufacturing of their electronic/silicon devices to China.

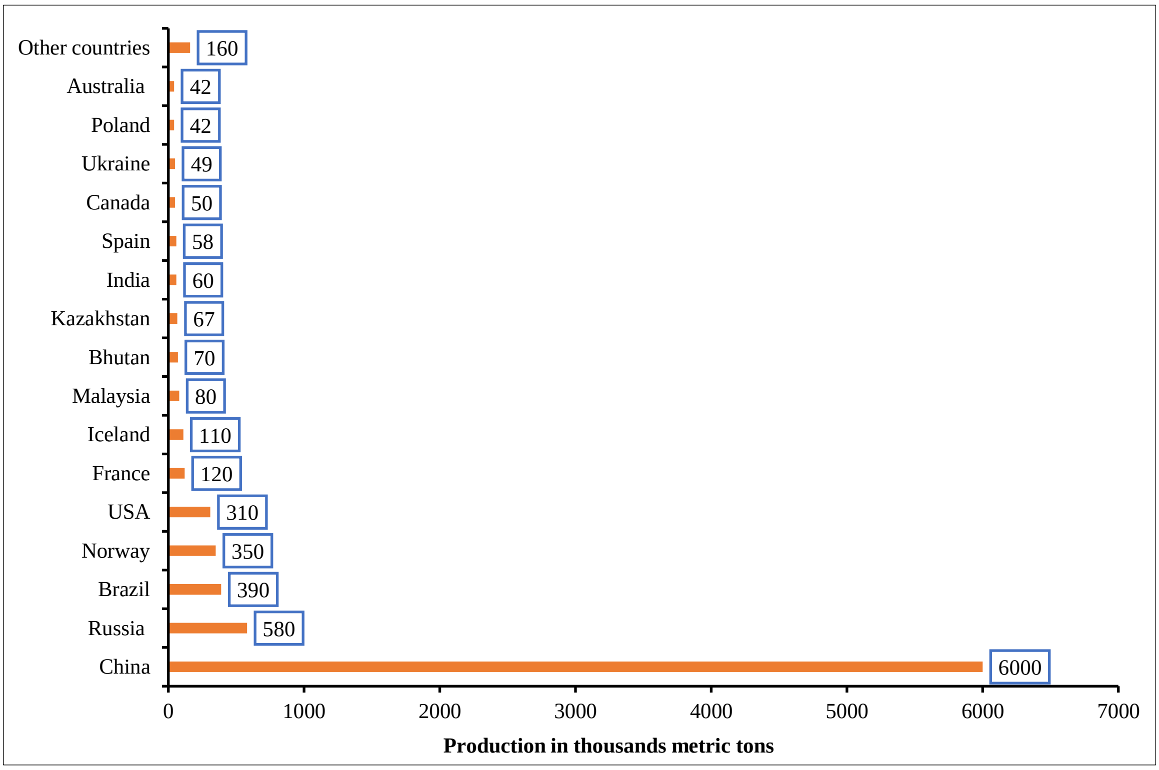

Figure 2. Worldwide silicon production in metric tons

3.3.2. Silica Fume

When silicon is extracted and refined metallurgically, silica fume (SF) is produced, as explained by Williams & Partheeban [21]. Non-biodegradable silicone goods used in electronics, medications, and cosmetics are discarded in open landfills. The disposal of SF in public areas has adverse health issues. Therefore, recycling such waste is a crucial concern.

The construction industry faces numerous challenges today, primarily due to rapid urbanization, depleting natural resources, and its adverse impact on climate change. The construction industry can utilize massive amounts of industrial solid waste in construction activities; one such waste is SF. The primary reason for choosing this waste is its acceptance and widespread practical implementation. The American Concrete Institute (ACI) describes SF as an ultra-minute amorphous fume generated industrially by reducing silicon dioxide with carbon in electric furnaces. The quartz of high purity, or ferro-silicate ores, was smelted at a temperature of up to 2000°C. After extracting the metal, the condensed amorphous silicon fumes or its alloys having silicon were collected, and silica fume was obtained by Singh et al. [59]. Equation 3 shows the breakdown of silicon dioxide during the production of SF in the furnace.

$$SiO_2+2C=Si+2CO \tag{3}$$

The complete stepwise industrial metallurgical extraction of silicon is graphically shown in Figure 3. The condensed silica dust's main component is more than 90% amorphous SiO_2 with a particle size of around 0.1 µm Mohyiddeen & Maya [60].

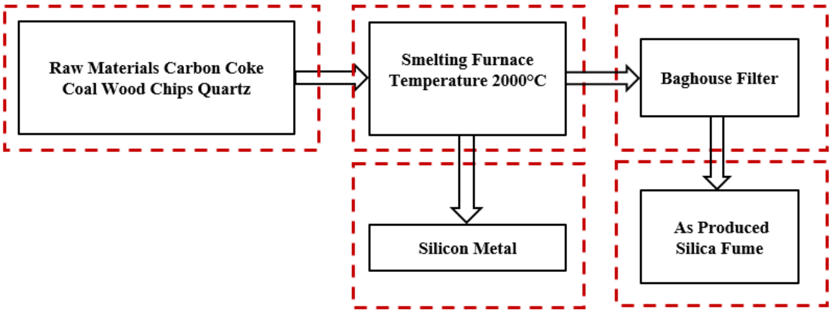

Figure 3. Silica fume production process

Adding SF to concrete enhances durability and internal micro pore spaces. It minimizes the permeability, ion diffusion, and amount of calcium hydroxide, subsequently providing exceptional resistance toward the chemical attack of sulfate. The amorphous and excellent physical properties of SiO_2 make this pozzolanic material very reactive. When the OPC within the concrete reacts, it liberates calcium hydroxide, where OH^- ions tend to diffuse as free radicals. In contrast, SF bonds with calcium hydroxide and makes a gel-like substance known as "calcium silicate hydrate," which also forms during the production of OPC, as shown in Equation 4.

$$2(3CaO{\cdot}SiO_2)+6H_2O = 3CaO \cdot SiO_2 \cdot 3H_2O + 3Ca(OH)_2 \tag{4}$$

Pozzolanic materials absorb calcium oxide and make the C-S-H gel phase, as seen in Equation 5.

$$3Ca(OH)_2+Si(OH)_2+SiO_2= 3CaO \cdot SiO_2 \cdot 3H_2O \tag{5}$$

This C-S-H binder gel packed the concrete's microstructure pores, which dense the internal structure, providing additional strength and enhancing the concrete's strength and durability, as shown in Figure 4. Luo et al. [61] suggested that replacing the cement paste with industrial SF (0-10%) of approximately 2.9–11.5 kg of cement in concrete production could save per cubic meter of concrete. In 2020, the global SF market reached USD 480.9 million, projected to reach USD 333.6 million by 2028 [45, 46]. According to the data, scientists promoted the utilization of SF waste. The new artificially produced resource will be more environmentally friendly, replacing OPC in the construction industry.

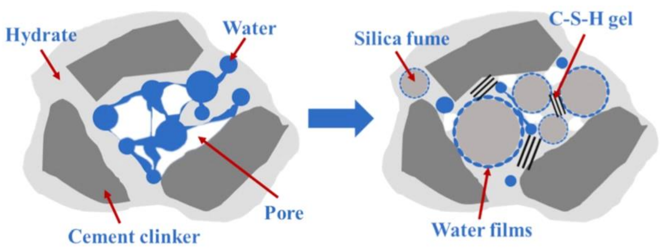

Figure 4. A pictorial depiction of concrete made with silica fume and OPC showing C-S-H gel binding effects in a study by Luo et al. [61]

3.3.2.1. Physical Properties of Silica Fume

The SF particles are primarily white and grey in color and spherical in shape, and more than 95% are less than one micrometer. The surface area of particles ranges from 13,000 to 30,000 m^2/kg [62–64]. The ordinary Portland cement (OPC) particles are roughly 100 times larger than the SF particles reported by Khan and Siddique [63]. The physical characteristics are shown in Table 2.

Table 2. Physical properties of silica fume

Properties	Mastali & Dalvand (2016) [65]	Hasan-Nattaj & Nematzadeh (2017) [66]	Fallah & Nematzadeh (2017) [67]	Wu et al. (2016) [68]	Ju et al. (2017) [69]	Soliman & Tagnit-Hamou (2017) [70]	Pedro et al. [71] (2017)
Specific gravity (g/cm^3)	2.21	1.9-2.3	2.21	2.2	-	2.2	-
Specific surface area (m^2/kg)	14,000	20,000-25,000	14,000	18,500	-	20,000	20,000
Particle size (nm)	-	229	229	-	200	150	-
Density (g/cm^3)	-	-	0.3-0.5	-	2.23	-	2

3.3.2.2. Chemical Properties of Silica Fume

Table 3 demonstrates trace amounts of iron, magnesium, and alkali oxides. The silicon oxide improves SF's cementitious properties and pozzolanic reactivity, which makes it suitable for replacing OPC in concrete. The chemical properties are shown in Table 3.

Table 3. Chemical properties of silica fume

Properties	Mastali & Dalvand (2016) [65]	Rostami & Behfarnia (2017) [72]	Karthikeyan & Dhinakaran (2018) [73]	Fallah & Nematzadeh (2017) [67]	Bajja et al. (2017) [74]	Wang et al. (2017) [75]	Wu et al. (2016) [68]
SiO_2	85-95	88-94	97.36	93	95	98.48	93.9
Al_2O_3	0.5-1.7	0.6-1.2	0.53	1.7	0.2	0.40	-
Fe_2O_3	0.4-2.0	0.3-1.6	0.15	1.2	0.4	0.03	0.59
MgO	0.1-0.9	0.95-1.8	0.79	1.0	0.3	0.40	0.27
K_2O	0.15-1.02	0.7-1.2	0.29	1.1	0.1	0.72	0.86
Na_2O	0.15-0.20	0.7-1.2	0.06	0.6	0.6	0.25	0.17
CaO	-	0.95-1.8	0.14	0.3	0.5	0.44	1.85
SO_3	-	-	0.51	-	-	0.42	0.42
pH	-	-	-	6.8-8.0	-	-	-
Moisture	-	-	-	0.01-0.4	-	-	-
Loss of ignition	-	-	-	-	2.5	0.90	0.90

4. Results and Discussion

This review paper utilized the SLR methodology to evaluate SF-based concrete environmental, engineering, and economic (EEE) management. The methodology part discussed the SLR methodology in detail. The discussion is presented based on the findings and interpretations of the previously published studies.

4.1. Silica Fume-based Concrete

In some countries, it's mandatory to utilize flyash up to certain limits in cement and concrete production. India announced that any coal-based thermal power plant must use 100% flyash in construction activities within 300 km of the thermal power plant [9, 13, 76–81]. SF can also be replaced by SCM in concrete manufacturing. Table 4 shows the key findings of different percentages of OPC replacement with SF (5–20%). Some recent studies have also investigated combinations of silica fume with desert sand and recycled crushed sand from demolished concrete [24, 82]. However, the performance of SF with sustainable desert and recycled crushed sand was highly remarkable, but the studies are scanty. Therefore, more research can be conducted in this area.

Table 4. Key findings of silica fume concrete at different percentages

References	OPC partially replaced with SF	Key findings
[82-92]	≤ 10	1. OPC used SF as an additive material for up to 10% of these studies. 2. The highest compressive strength was observed at 20% RFA and 10% SF combination. 3. Using SF with RFA in concrete intensifies the compressive strength compared to the reference mixes. 4. During the experiments, SF successfully controlled chloride ion penetration and the solution temperature, indicating that ion movement in the concrete was controlled.
[33, 89, 93-97]	≤ Up to15	5. The SF was utilized in these studies up to 15% by weight of OPC. 6. The research shows that the higher SF content at 15% in the marine environment reduced the chloride diffusion coefficient in concrete. 7. The experiments projected valuable information on SF addition in 15%. 8. A positive increment was observed in splitting tensile and FS by adding SF at 15%. 9. The study results revealed that adding SF had improved the durability against chemical deterioration.
[34, 98-105]	≤ Up to 20	10. SF replaced the OPC in different percentages, up to 20%. 11. Up to 20%, SF replacement by weight of OPC shows a slight increment in compressive strength to control mixes. 12. The study's results revealed that a higher percentage of SF, such as 20%, did not affect compressive strength. 13. The replacement of up to 20% of SF by OPC made concrete more economical and sustainable. 14. It has been concluded from the studies that more than 20% of SF is not recommended in concrete production.

4.1.1. Engineering Characteristics of Silica Fume-based Concrete

Relative Compressive Strength

The SF percentages against relative compressive strength are compared to previously published studies shown in Figure 5. The SLR of this study disclosed the replacement percentages of OPC with SF of 5–20%. The fluctuation in compressive strength against SF percentage was reported by published studies in Figure 5. A significant increase was revealed, up to 15% incorporation of SF in compressive strength. The maximum relative compressive strength at 5, 10, 12.5, 15, and 20% replacement of OPC with SF was 16, 29, 27, 16, and 2% [100, 106, 107]. The replacement of OPC with SF at 5% compressive strength was increased further; at 10%, more increments were observed. Up to 15% increments were maintained in SF-based concrete. When the replacement ratio reached 20%, a reduction in increment was shown in Figure 5.

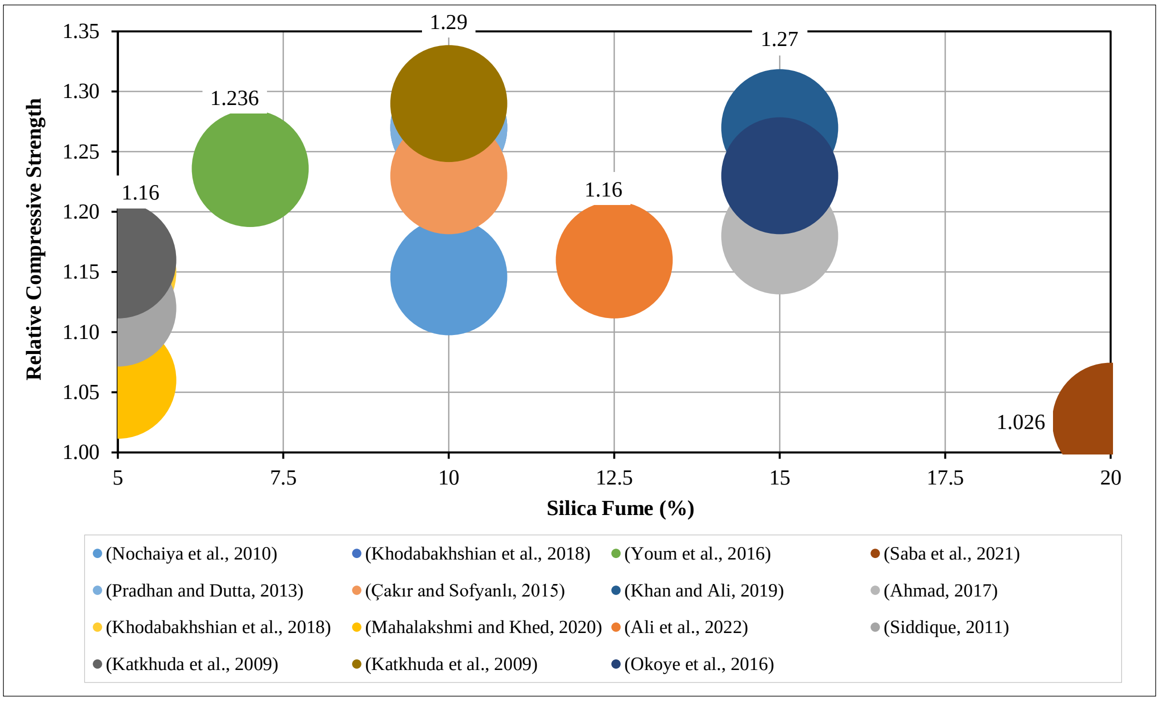

Figure 5. Comparison of the ratio of relative compressive strength of SF-based concrete

Compressive strength was reported to rise as and when the substitution of OPC with SF increased up to 10%. Compressive strength increased by about 23% at a 7% replacement ratio. The increase in compressive strength at a 10% replacement ratio was 29, 27, 27, 23, and 15%, as shown in Figure 5. The research findings [85, 108] indicate an exact 27% increase in compressive strength at a 10% replacement ratio of OPC with SF. The highest 29% increment in compressive strength was reported again at 10% replacement of OPC with SF, as studied by Katkhuda et al. [106]. Different design mixes and the use of many SCMs included in the same mix are the causes of strength variation at the same replacement ratio. At 15%, the results of studies [97, 109, 110] increased the compressive strength by approximately 18, 27, and 23%, respectively. The lowest increment in compression strength was seen at the higher % replacement ratio of 20%, as studied by Saba et al. [100].

As a result of the discussion, most studies [95, 98, 99, 101, 103, 105] did not recommend the higher replacement (≥ 20%) of OPC with SF. An excellent improvement in the compressive strength was observed when the replacement ratios were between (7 to 15%). A threshold of compressive strength improvement was recorded at a 10% replacement ratio. It was discovered that adding SF at lower concentrations, between (7 to 15%) results in denser microstructure and an enhancement in compressive strength (i.e., additional C-S-H gel produced). Adding the right amount of SF will also cause compaction, and the fineness of the SF will create an enormous surface area that will result in a solid bond with the cement. As a result, the mix's compressive strength will rise relative to all control mixes.

Relative Splitting Tensile Strength

The relative splitting tensile strength (STS) values at various SF percentages of 5%, 7.5%, 10%, 12.5%, 15%, and 20%, according to published studies [33, 98, 101, 102, 111, 112] are presented in Figure 6. The highest increment in STS results was achieved at 33%, 39%, and 39% by replacing 7.5%, 10%, and 12.5% of OPC with SF in SF-based concrete. At 15% incorporation of SF in SF-based concrete, 29%, 28%, and 26% increases were seen in STS values studied by [33, 106, 107]. A higher replacement ratio of 20% of OPC with SF has also been implemented in recent research by [100, 101], which found almost 21% and 29% increments in STS values. The concrete's STS results estimate the sample's maximum load without cracking. Concrete samples' paste quality and interfacial transition zone depend on fine aggregate quality. Incorporating SF percentages improves the paste quality and enhances the bond at the interface, ultimately increasing the STS values.

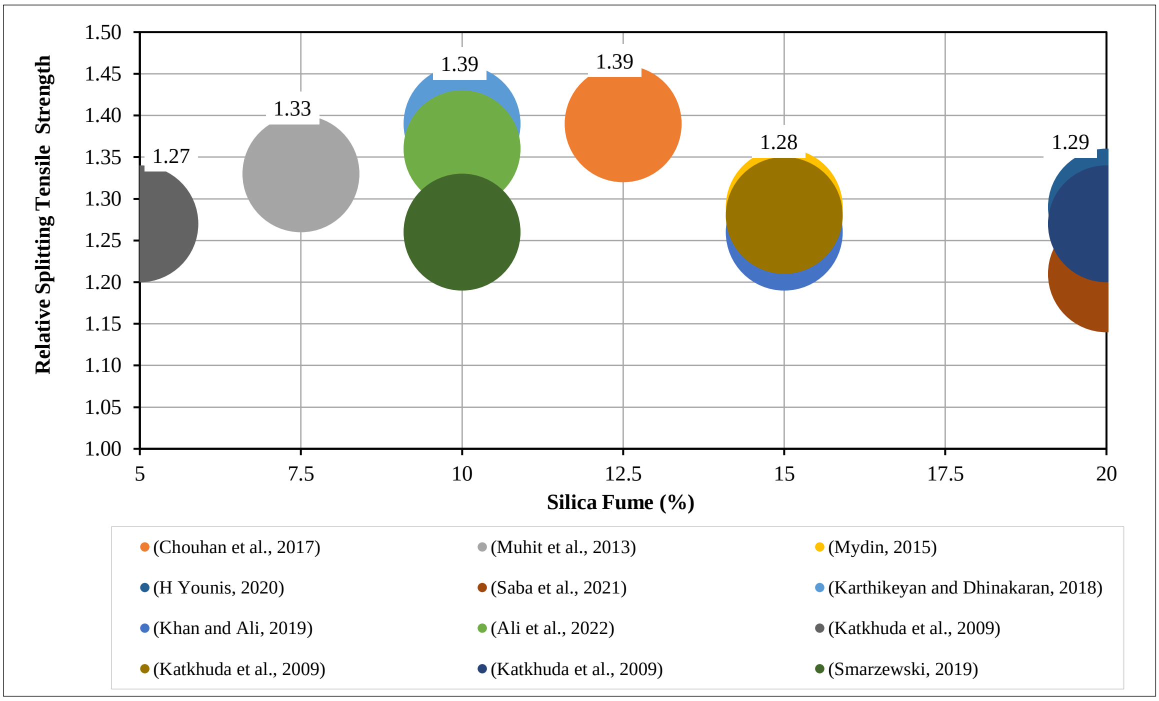

Figure 6. Comparison of the ratio of SF-based concrete percentage to relative splitting tensile strength

Relative Flexural Strength

Figure 7 displays the relative flexural strength (FS) versus various SF percentages. In the study [111], the FS at 7.5% replacement of OPC with SF showed a significant increase of about 35% in FS value. At 10% incorporation of SF, the highest gain of 37% and 40% in FS was reported by [111, 113]. Not many studies have seen a 15% substitution of SF; a study by Othuman Mydin [33] achieved a 28% increment in FS. Even a higher replacement ratio of 20% OPC with SF revealed significant improvement if FS values of 30, 26, and 28% were studied by [100, 102, 111], respectively. Hence, replacing OPC with SF by up to 20% dramatically impacts the FS values of SF-based concrete.

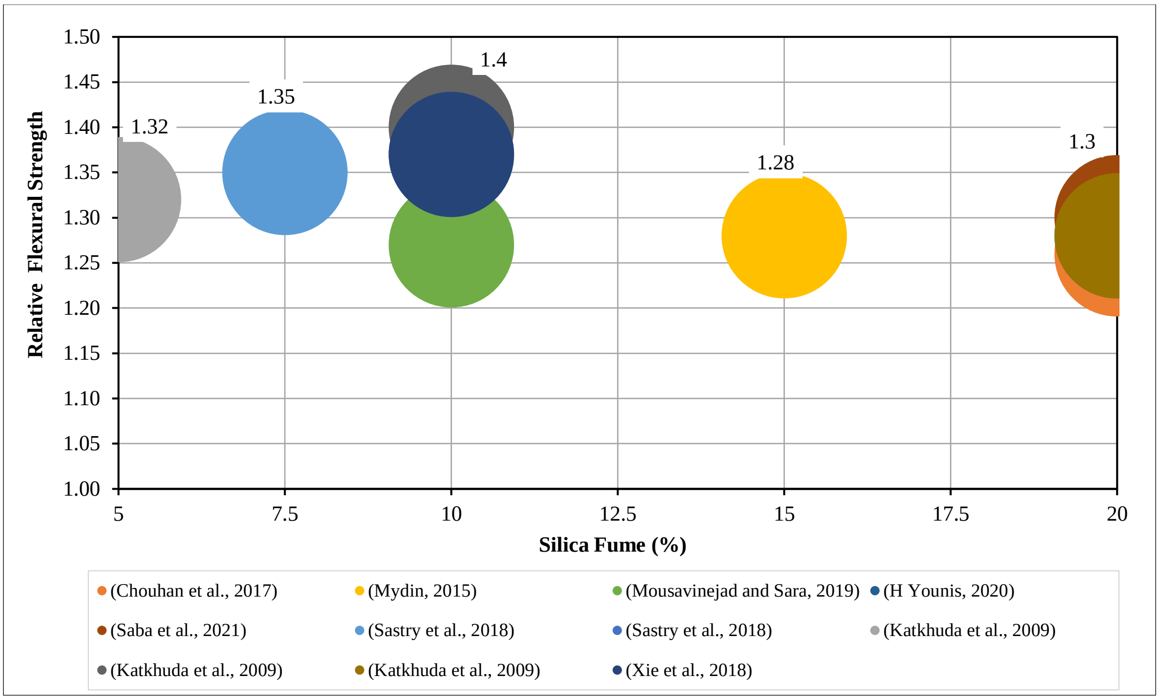

Figure 7. Comparison of the ratio of relative flexural strength of SF-based concrete

4.1.2. Durability Characteristics of Silica Fume-based Concrete

The durability characteristics of hardened concrete, such as density, porosity, water absorption, effect on flammability, and acid attack, were examined. The behavior of hardened concrete at high temperatures, its ability to absorb water, its density, and its voids have all been examined. The results of the studies [32, 72, 82, 114–118] show the most significant outcomes at 10% OPC replacement with SF. After carefully examining the durability behaviors of SF-based concrete, it was discovered that 10% of OPC replacement with SF revealed the best outcomes. The results of earlier research show that up to 20% utilization of SF also has positive durability characteristics. However, the increment rate decreased when the replacement ratio increased above 10% in SF-based concrete. The heat of hydration is decreased, and the setting time is increased when OPC is partially substituted with SF without affecting the strength. The replacement of OPC with SF in new concrete is positive up to optimized values since it has a higher density, less water absorption, and porosity [24, 116]. Table 5 shows SF-based concrete durability characteristics with 5-20% SF incorporation in SF-based concrete.

Table 5. SF-based concrete durability

Studies	Durability parameters		Important conclusions
	Properties	Description	
[71, 72, 82, 95, 114-116, 119]	Density, water absorption, and porosity	OPC is substituted with SF at 5, 7.5, 10, 12, 15, and 20%	1. The experimental findings showed a decline in the void ratio, which decreased water absorption. The SF fills the holes with smaller particle sizes, enhancing density and, eventually, durability. 2. Replacing 10% of OPC with SF had the best water absorption, voids, and density results in cured concrete. 3. Results from earlier studies show that the characteristics of the concrete are diminished when SF is replaced with more than 20% of the cement's weight. 4. The SF particle's tiny size fills the gaps in cement mortar. More than 20% of SF increases cement mortar's number of voids, which makes these particles more brittle. 5. Adding (more than 20%) SF will increase the volume of voids, decreasing the solid concentration rather than filling the gaps and boosting packing density. As a result, the concrete's resilience will be reduced.
[113, 120, 121]	Concrete hardened properties at ambient temperature	100, 200, 300, 400, 500, and 600ºC	6. Normal concrete strength and silica-based concrete do not degrade as the temperature rises to 200°C. 7. Regular concrete behaved the same way as SF-based concrete up to 300°C regarding its toughened qualities. 8. The compressive strength of SF-based concrete rapidly declines after 400°C. 9. Above 400°C, both standard and SF-based concrete experience significant weight loss. 10. SF-based concrete had more muscular strength and weight loss reduction rates at 600°C than ordinary concrete.

The findings of the studies [24, 113, 120, 121] show that the performance of SF-based concrete at high temperatures was also examined as a durability factor. Up to 300°C, SF-based concrete exhibited minimal strength loss compared to standard concrete. The compressive strength of standard and SF-based concrete gradually reduces at 400°C. At 600°C, SF-based concrete's strength and weight loss is significantly lower than standard concrete's.

The results of durability characteristics are satisfactory in all replacement ratios (5–20%). However, earlier research was used to find future studies' optimal parameters. This rule of thumb will alter the durability of SF-based concrete by employing new materials rather than recycled ones. The discussion concludes that each design combination must optimize its unique SF combination. As a result, before using the SF percentages for commercial reasons, optimizing individually for each project is recommended.

4.2. Economic Aspect

4.2.1.Production Cost of Concrete with Silica Fume Percentages

The amount of OPC used in the concrete depends on the type of grade and design mixes. Approximately 0.3 tons of OPC per ton of concrete is used in the ready-mix concrete plant, as disclosed by Akhtar et al. [24]. IEA [41] reported that 0.5–0.6 tons of CO_2 are emitted per ton of OPC production; OPC companies' reports indicate a value of around (0.6–0.7) tons of CO_2 per ton of OPC. For the calculation of CO_2 emission, the average value of 0.6 was taken by multiplying the average value of 0.6 by the total OPC production to obtain the total CO_2 emission from the cement industry annually. For the present study, results and interpretation of the selected articles [83, 101, 107, 122] at 0%SF*, 5%SF, 10%SF, 12.5%SF, 15%SF, and 20%SF were utilized in place of OPC to reduce CO_2 emissions from the cement industry. The control mix was taken at 0%SF* for comparison with other studies.

Based on the international market price, the 1 m^3 production cost of the concrete mixes with 5%SF, 10%SF, 12.5%SF, 15%SF, and 20%SF is estimated in Table 6. The cost of developed concrete mixes with and without silica fume has been calculated based on the rate at which their ingredients were purchased and the cost of the materials used in the United States (US) ($/kg). The production cost of 1 m^3 of developed design mix concrete was estimated by multiplying the quantity of each ingredient in kg/m^3 by the cost of the ingredients in US dollars ($/kg). The final cost of each mix is computed in US dollars. The total cost of the mixes at 5%SF, 10%SF, 12.5%SF, 15%SF, and 20%SF with and without SF is estimated in Table 5. The control mix at 0%SF* cost was approximately 57.47 dollars, and all-natural ingredients were mixed without SF content. The cost of the mixes at 5%SF, 10%SF, 12.5%SF, 15%SF, and 20%SF was estimated at 60.56 $, 61.16 $, 67.72$, 70.02 $, and 71.82 $, respectively. It has been observed that the 1 m^3 production cost of the newly developed mixes at 5%SF, 10%SF, 12.5%SF, 15%SF, and 20%SF is higher than the control mix (0%SF* without SF content).

Table 6. Production cost of 1 m^3 of concrete with silica fume percentages

Concrete ingredient	Ingredients cost (US $/kg)	Mahalakshmi et al. (2020) [122]	Karthikeyan & Dhinakaran (2018) [73]	Akhtar et al. (2023) [18]	Khan & Ali (2019) [107]	Ismail et al. (2020) [101]
		5%SF	10%SF	12.5%SF*	15%SF	20%SF
Fine aggregate (sand)	0.02	15.10	12.14	15.04	16.20	14.78
Coarse aggregate	0.010	9.54	12.18	9.58	8.10	10.34
Cement (OPC)	0.067	28.62	21.44	27.31	26.80	23.78
Silica fume (SF)	0.267	6.10	13.20	15.55	16.02	19.12
Admixture by weight of cement (%)	0.40	1.20	2.20	0.24	2.90	3.80
Total cost in (US $)		60.56	61.16	67.72	70.02	71.82

Compared with the control mix of 0%SF*, the cost of developed concrete at 5%SF, 10%SF, 12.5%SF, 15%SF, and 20%SF is higher. As mentioned in the study by Akhtar et al. [24], SF costs are four times higher than the OPC. Replacing 5%, 10%, 12.5%, 15%, and 20% OPC with SF increased the cost of mixes. The cost of the mixes 5%SF, 10%SF, 12.5%SF, 15%SF, and 20%SF was about 5%, 7%, 17.8%, 21%, and 25% higher than the control mix at 0%SF*. It can be concluded from the discussion that the increase in SF content in the design mix of concrete increases the cost. The higher the increment, the more the cost of concrete is revealed.

4.2.2. Benefit-cost Ratio of Concrete at Different Silica Fume Percentages

The cost, engineering properties, and benefit-cost ratio comparison of the mixes with different SF percentages in concrete is presented in Table 7. The prices of the materials used in concrete manufacturing are taken as per the prevailing international market rates. The cost has been converted into US dollars for comparison with the world scenario. The production cost of 1 m^3 of concrete from the selected published studies in the present study is mentioned in Table 6.

Table 7. Benefit-cost ratio of mixes with different SF percentages with respect to the control mix

Parameters	Mahalakshmi et al. (2020) [122]	Karthikeyan & Dhinakaran (2018) [73]	Akhtar et al. (2023) [18]	Khan & Ali (2019) [107]	Ismail et al. (2020) [101]
w.r.t. control mix 0%SF*	5%SF*	10%SF	12.5%SF	15%SF	20%SF
Change in compressive strength	0.059	0.278	0.320	0.230	0.036
Change in splitting tensile strength	0.116	0.368	0.204	0.280	0.082
Change in flexural strength	-	0.390	-	0.680	0.052
Change in modulus of elasticity	0.086	-	-	0.160	-
Weightage factor (10) multiplied by each parameter	1	2	3	4	5
Change in compressive strength	0.59	2.78	3.20	2.3	0.36
Change in splitting tensile strength	1.16	3.68	2.04	2.8	0.82
Change in flexural strength	-	3.90	-	6.8	0.52
Change in modulus of elasticity	0.86	-	-	1.6	-
Benefit	Σ 1 = 2.61	Σ 2 = 10.36	Σ 3 = 5.24	Σ 4 = 13.5	Σ 5 = 1.7
Cost ($)	60.56	61.16	67.72	70.02	71.82
$\frac{\text{Benefit}}{\text{Cost}} \times 100$	4.31	16.94	7.74	19.28	2.36

Table 7 compares the parameters of the selected studies with respect to (w.r.t.) the control mix for each study, as we know that the strength characteristics are the most important characteristics to evaluate the concrete value. For this reason, the four most general and effective parameters, compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity, were selected to compare the benefit-cost ratio of the concrete at 5%, 10%, 12.5%, 15%, and 20% replacement of OPC with SF. The value of selected parameters, compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity, was considered at 28 days of curing. The negative sign represents a percentage decrease, and positive values indicate a percentage increase. It can be seen from Table 7 that all parameters show positive values, indicating that at each replacement value, increments in the selected parameters ranged from 5 to 20%.

The benefit-cost ratio of the mixes at 5%, 10%, 12.5%, 15%, and 20% SF studied by [73, 101, 107, 122] compared with each mix control value without SF is shown in Table 7. The values of the benefit-cost ratio were computed by Equation 6 in Table 7.

$$\text{Benefit-cost ratio} = \frac{\text{Benefit}}{\text{Cost}} \times 100 \tag{6}$$

The weightage factor measures the importance of specific properties of concrete to bring them to the same scale of calculations. There are no specific guidelines concerning the weightage factor for the benefit-cost ratio of concrete. Therefore, the weightage factor is taken according to the latest studies [123, 124]. This study considers parameters such as compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity equally important. Therefore, the highest weighting factor of 10 is given to each parameter. The benefit-cost ratio of concrete is the sum of the benefits for compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity divided by the cost.

The benefit-cost ratio in the studies [73, 101, 107, 122] was computed (4.31, 16.94, 7.74, 19.28, and 2.36) at 5%, 10, 12.5, 15, and 20%, respectively. The highest benefit-cost ratio was observed at 15% replacement of OPC with SF, and the lowest was at 20%. However, compared with the selected parameters, the study by Khan & Ali [107] at 15% SF incorporation studied all parameters. All parameters show positive effects, with all SF percentages ranging from 5 to 20%. By this fact, we can conclude that the higher the parameters, the higher the benefit-cost ratio. Another point is that the greater the gain in the parameters, the greater the benefit-cost ratio. The research by Mahalakshmi & Khed [122] and Younis et al. [101] studied three parameters and achieved a benefit-cost ratio of 4.31 and 2.36. Akhtar et al. [18] studied only two parameters and achieved a benefit-cost ratio of 7.74. The discussion leads us to the conclusion that two factors are crucial for maximizing benefits: the number of parameters and the gain in each parameter.

The confirmation of improvement in concrete properties by adding SF percentages was revealed from published studies cited in this review article. A most comprehensive recent review by Akhtar et al. [24] shows a positive finding for the replacement of OPC by SF. The optimum level of 10% OPC replacement with SF was discovered. Incorporating the optimum level of SF in sustainable concrete has proved to increase the benefit-cost ratio in terms of enhanced parameters of prepared sustainable SF-based concrete with reference to the control mix without SF. The benefit-cost ratio is a new way of analyzing OPC replacement with SF in SF-based concrete. However, the cost of concrete containing SF is higher than that of the control mix without SF content. The benefit-cost ratio analysis reveals the economically beneficial effects that can be achieved in a developed sustainable SF-based concrete (5–20%) SF combination. This study gives a different way of analyzing the utilization of SF at higher percentages. As shown in Table 7, the benefit-cost ratio is positive, up to a 20% replacement of OPC with SF. Hence, it can be concluded from this analysis that higher replacement is also beneficial in terms of the benefit-cost ratio.

5. Recommendation for Future Research

This review article presents SLR on SF-based concrete. The SLR shows several researchers have successfully utilized SF to partially replace OPC (5–20%). The studies on the higher replacement of OPC with SF in SF-based concrete are short. A benefit-cost ratio analysis was also done in this review study. It revealed the economically beneficial effects that can be achieved in SF-based concrete, up to a 20% replacement of OPC with SF. This review study suggested that the higher replacement of OPC with SF is also beneficial in terms of the benefit-cost ratio.

Insufficient data on the combined effects of SF with sustainable sand, such as recycled fine aggregate and desert sand, in making SF-based concrete is available. It has been suggested that sustainable sand, such as recycled crushed sand from demolished concrete and desert sand, can be combined with a higher replacement of SF. Therefore, a research gap has been found for future research by replacing higher percentages of OPC with SF combined with sustainable sand in new SF-based concrete. Successful utilization of higher incorporation of SF combined with sustainable sand would be a green step towards sustainability. This recommendation will open a new domain, solve the issues of excessive natural river sand mining, and help reduce CO_2 emissions from the cement industry. If policymakers in every country enforce better environmental laws, they could save millions of tons of OPC annually, and utilizing SF helps to manage CO_2 emissions globally. The following are recommendations for future experimental research work:

- It is recommended that silica fume be replaced in design mix concrete at a higher replacement ratio of up to 20%; however, proper optimization is required.
- A study can be conducted to observe the combined effect of sustainable sand replacement with natural river sand along with an optimized silica fume percentage.
- In-depth knowledge of concrete's strength and durability parameters can be examined using sustainable sand with a higher silica fume replacement.
- It is proposed to develop a cost analysis and sustainability measurement model when higher silica fume replacement is combined with sustainable sand.

6. Conclusions

This review article investigates silica fume replacement with cement in SF-based concrete production. The successful utilization of silica fume can combat the issues of excessive CO_2 emissions, climate change, and the ecosystem. The detailed conclusions drawn after data extraction from 124 peer-reviewed, high-quality studies are below.

- The mixes with all combinations of (5–20%) cement replacement with silica fume showed a positive increment in compressive strength. The average increment of 24% was seen at 10% incorporation of silica fume.
- A splitting tensile and flexural strength increased when silica fume was replaced between (5-20%). The highest increase of 37% in splitting tensile strength and 40% in flexural strength was seen at 10% incorporation of silica fume. Splitting tensile and flexural strength increments were also observed at higher replacement of 20% cement with silica, by 29% and 30%, respectively.
- All (5–20%) silica fume incorporation positively affected the durability of SF-based concrete. At 10%, cement replacement with silica fume revealed the best results.
- The benefit-cost ratio analysis reveals the economically beneficial effects that can be achieved in SF-based concrete, up to a 20% replacement of cement with silica fume.

Hence, it can be concluded from this review study that the higher cement replacement with silica fume is also beneficial in terms of the benefit-cost ratio. Finally, we can conclude that 10% silica fume incorporation is the best replacement ratio discovered by past studies. However, benefit-cost ratio analysis revealed that up to 20% of silica fume can be replaced with cement. Replacing more cement with silica fume produces more sustainable concrete, which would be an environmental savior.

7. Declarations

7.1. Author Contributions

Conceptualization, M.N.A. and A.M.A.; methodology, M.N.A.; validation, A.M.A.; and M.N.A.; formal analysis, M.N.A.; investigation, A.M.A.; resources, A.M.A.; data curation, M.N.A.; writing—original draft preparation, M.N.A.; writing—review and editing, A.M.A.; visualization, A.M.A.; supervision, M.N.A.; funding acquisition, A.M.A. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

Data presented in this study is available in the article.

7.3. Funding

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7.4. Conflicts of Interest

The authors declare no conflict of interest.

8. References

[1] Roser, M., Ritchie, H., Ortiz-Ospina, E., & Rodés-Guirao, L. (2017). World Population Growth, Our World in Data. 2017. Available online: https://ourworldindata.org/world-population-growth (accessed on January 2023).

[2] United Nations. (2013). World population prospects: the 2012 revision. Department of Economic and Social Affairs, United Nations, New York, United States.

[3] Bongaarts, J. (2020). United Nations Department of Economic and Social Affairs, Population Division World Family Planning 2020: Highlights, United Nations Publications. Population and Development Review, 46(4), 857–858. doi:10.1111/padr.12377.

[4] Akhtar, M. N., Bani-Hani, K. A., Akhtar, J. N., Khan, R. A., Nejem, J. K., & Zaidi, K. (2022). Flyash-based bricks: an environmental savior—a critical review. Journal of Material Cycles and Waste Management, 24(5), 1663–1678. doi:10.1007/s10163-022-01436-3.

[5] Ahmad Khan, R., Nisar Akhtar, J., Ahmad Khan, R., & Nadeem Akhtar, M. (2023). Experimental study on fine-crushed stone dust a solid waste as a partial replacement of cement. Materials Today: Proceedings. doi:10.1016/j.matpr.2023.03.222.

[6] Alam, J., Khan, M., & Akhtar, M. (2013). Fly ash based brick tiles: An experimental study. International Journal of Emerging Trends in Engineering and Development, 6(3), 35-44.

[7] Ritchie, H., & Roser, M. (2018). Urbanization; Our World in Data. 2018. Available online: https://ourworldindata.org/how-urban-is-the-world (accessed on June 2023).

[8] Akhtar, J. N., Alam, J., & Akhtar, M. N. (2010). An experimental study on fibre reinforced fly ash based lime bricks. International Journal of the Physical Sciences, 5(11), 1688-1695.

[9] Akhtar, M. N., & Akhtar, J. N. (2018). Suitability of Class F Flyash for Construction Industry: An Indian Scenario. International Journal of Structural and Construction Engineering, 12(9), 892-897.

[10] Akhtar, M. N., Hattamleh, O., & Akhtar, J. N. (2017). Feasibility of coal fly ash based bricks and roof tiles as construction materials: A review. MATEC Web of Conferences, 120, 3008. doi:10.1051/matecconf/201712003008.

[11] Rasheed, R., Tahir, F., Afzaal, M., & Ahmad, S. R. (2022). Decomposition analytics of carbon emissions by cement manufacturing – a way forward towards carbon neutrality in a developing country. Environmental Science and Pollution Research, 29(32), 49429–49438. doi:10.1007/s11356-022-20797-8.

[12] Devi, K. S., Lakshmi, V. V., & Alakanandana, A. (2017). Impacts of cement industry on environment-an overview. Asia Pacific Journal of Research, 1, 156-161.

[13] Akhtar, M. N., AKhtar, J. N., & Hattamleh, O. (2013). The Study of Fibre Reinforced Fly Ash Lime Stone Dust Bricks With Glass Powder. International Journal of Engineering and Advanced Technology, 3(1), 314-319.

[14] Vig, N., Mor, S., & Ravindra, K. (2023). The multiple value characteristics of fly ash from Indian coal thermal power plants: a review. Environmental Monitoring and Assessment, 195(1), 33. doi:10.1007/s10661-022-10473-2.

[15] Habert, G. (2014). Assessing the environmental impact of conventional and 'green' cement production. Eco-Efficient Construction and Building Materials, 199–238, Woodhead Publishing, Sawston, United Kingdom. doi:10.1533/9780857097729.2.199.

[16] Wojtacha-Rychter, K., Kucharski, P., & Smolinski, A. (2021). Conventional and alternative sources of thermal energy in the production of cement—an impact on CO_2 emission. Energies, 14(6), 1539. doi:10.3390/en14061539.

[17] Henrion, L., Zhang, D., Li, V. C., & Sick, V. (2021). Bendable concrete and other CO_2-infused cement mixes could dramatically cut global emissions. World Economic Forum, Carlton, Australia. Available online: https://theconversation.com/bendable-concrete-and-other-co2-infused-cement-mixes-could-dramatically-cut-global-emissions-152544 (accessed on July 2023).

[18] Akhtar, M. N., Jameel, M., Ibrahim, Z., Muhamad Bunnori, N., & Bani-Hani, K. A. (2023). Development of sustainable modified sand concrete: An experimental study. Ain Shams Engineering Journal, 102331. doi:10.1016/j.asej.2023.102331.

[19] Akhtar, J. N., & Akhtar, M. N. (2014). Enhancement in properties of concrete with demolished waste aggregate. GE-International Journal of Engineering Research, 2(9), 73-83.

[20] Jiang, X., Xiao, R., Bai, Y., Huang, B., & Ma, Y. (2022). Influence of waste glass powder as a supplementary cementitious material (SCM) on physical and mechanical properties of cement paste under high temperatures. Journal of Cleaner Production, 340, 130778. doi:10.1016/j.jclepro.2022.130778.

[21] Williams, K. C., & Partheeban, P. (2018). An experimental and numerical approach in strength prediction of reclaimed rubber concrete. Advances in Concrete Construction, 6(1), 87–102. doi:10.12989/acc.2018.6.1.087.

[22] Akhtar, M., Halahla, A., & Almasri, A. (2021). Experimental Study on Compressive Strength of Recycled Aggregate Concrete under High Temperature. Structural Durability & Health Monitoring, 15(4), 335–348. doi:10.32604/sdhm.2021.015988.

[23] Akhtar, M. N., Al-Shamrani, A. M., Jameel, M., Khan, N. A., Ibrahim, Z., & Akhtar, J. N. (2021). Stability and permeability characteristics of porous asphalt pavement: An experimental case study. Case Studies in Construction Materials, 15, 591. doi:10.1016/j.cscm.2021.e00591.

[24] Akhtar, M. N., Jameel, M., Ibrahim, Z., & Bunnori, N. M. (2022). Incorporation of recycled aggregates and silica fume in concrete: an environmental savior-a systematic review. Journal of Materials Research and Technology, 20, 4525–4544. doi:10.1016/j.jmrt.2022.09.021.

[25] Nisar Akhtar, J., Ahmad Khan, R., Ahmad Khan, R., Nadeem Akhtar, M., & Thomas, B. S. (2023). A comparative study of strength and durability characteristics of concrete and mortar admixture by bacterial calcite precipitation: A review. Materials Today: Proceedings. doi:10.1016/j.matpr.2023.03.490.

[26] Vijayan, D. S., Devarajan, P., & Sivasuriyan, A. (2023). A review on eminent application and performance of nano based silica and silica fume in the cement concrete. Sustainable Energy Technologies and Assessments, 56, 103105. doi:10.1016/j.seta.2023.103105.

[27] Li, B., Gao, A., Li, Y., Xiao, H., Chen, N., Xia, D., Wang, S., & Li, C. (2023). Effect of silica fume content on the mechanical strengths, compressive stress–strain behavior and microstructures of geopolymeric recycled aggregate concrete. Construction and Building Materials, 384, 131417. doi:10.1016/j.conbuildmat.2023.131417.

[28] Chishi, A. K., & Gautam, L. (2023). Sustainable use of silica fume in green cement concrete production: a review. Innovative Infrastructure Solutions, 8(7), 195. doi:10.1007/s41062-023-01164-z.

[29] Etli, S. (2023). Evaluation of the effect of silica fume on the fresh, mechanical and durability properties of self-compacting concrete produced by using waste rubber as fine aggregate. Journal of Cleaner Production, 384, 135590. doi:10.1016/j.jclepro.2022.135590.

[30] Ashraf, M., Iqbal, M. F., Rauf, M., Ashraf, M. U., Ulhaq, A., Muhammad, H., & Liu, Q. Feng. (2022). Developing a sustainable concrete incorporating bentonite clay and silica fume: Mechanical and durability performance. Journal of Cleaner Production, 337, 130315. doi:10.1016/j.jclepro.2021.130315.

[31] Fallah-Valukolaee, S., Mousavi, R., Arjomandi, A., Nematzadeh, M., & Kazemi, M. (2022). A comparative study of mechanical properties and life cycle assessment of high-strength concrete containing silica fume and nanosilica as a partial cement replacement. Structures, 46, 838–851. doi:10.1016/j.istruc.2022.10.024.

[32] Ahmad, S., Baghabra Al-Amoudi, O. S., Khan, S. M. S., & Maslehuddin, M. (2022). Effect of silica fume inclusion on the strength, shrinkage and durability characteristics of natural pozzolan-based cement concrete. Case Studies in Construction Materials, 17, 1255. doi:10.1016/j.cscm.2022.e01255.

[33] Othuman Mydin, M. A. (2015). Effect of silica fume and wood ash additions on flexural and splitting tensile strength of lightweight foamed concrete. Jurnal Teknologi, 74(1), 125–129. doi:10.11113/jt.v74.3653.

[34] Srivastava, V., Kumar, R., Agarwal, V. C., & Mehta, P. K. (2014). Effect of silica fume on workability and compressive strength of OPC concrete. Journal of Environmental Nanotechnology, 3(2), 32-35. doi:10.13074/jent.2014.09.143086.

[35] Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Journal of Clinical Epidemiology, 62(10), 1006–1012. doi:10.1016/j.jclinepi.2009.06.005.

[36] Callery, S. (2021). What is the greenhouse effect?, Global Climate Change, NASA Jet Propulsion Laboratory, Pasadena, United States. Available online: https://climate.nasa.gov/faq/19/what-is-the-greenhouse-effect/ (accessed on September 2023).

[37] Benhelal, E., Shamsaei, E., & Rashid, M. I. (2021). Challenges against CO2 abatement strategies in cement industry: A review. Journal of Environmental Sciences (China), 104, 84–101. doi:10.1016/j.jes.2020.11.020.

[38] Perrone, T. (2010). The history of climate change conferences, also known as COPs. Life Gate, Milano – Italy. Available online: https://www.lifegate.com/history-climate-change-conferences (accessed on September 2023).

[39] Hunter, D. B., Salzman, J. E., & Zaelke, D. (2021). Glasgow Climate Summit: Cop26. SSRN Electronic Journal. doi:10.2139/ssrn.4005648.

[40] Wilson, N., & Rae, K. (2022). Report from a COP-26 public participation event. Mental Health Foundation, Glasgow, Scotland.

[41] IEA. (2020). Reducing CO_2 Emissions while Producing Enough Cement to Meet Demand Is a Global Challenge, Especially since Demand Growth Is Expected to Resume. International Energy Agency (IEA), Paris, France. Available online: https://www.iea.org/energy-system/industry/cement (accessed on 13 March 2022).

[42] Worrell, E., Price, L., Martin, N., Hendriks, C., & Meida, L. O. (2001). Carbon dioxide emissions from the global cement industry. Annual Review of Energy and the Environment, 26(1), 303–329. doi:10.1146/annurev.energy.26.1.303.

[43] Mishra, L. C., & Shukla, K. N. (1986). Effects of fly ash deposition on growth, metabolism and dry matter production of maize and soybean. Environmental Pollution Series A, Ecological and Biological, 42(1), 1–13. doi:10.1016/0143-1471(86)90040-1.

[44] Falah, M. W., Hafedh, A. A., Hussein, S. A., Al-Khafaji, Z. S., Shubbar, A. A., & Nasr, M. S. (2021). The combined effect of CKD and silica fume on the mechanical and durability performance of cement mortar. Key Engineering Materials, 895, 59–67. doi:10.4028/www.scientific.net/KEM.895.59.

[45] Andrew, R. M. (2018). Global CO_2 emissions from cement production. Earth System Science Data, 10(1), 195–217. doi:10.5194/essd-10-195-2018.

[46] Andrew, R. M. (2019). Global CO_2 emissions from cement production, 1928–2018. Earth System Science Data, 11(4), 1675–1710. doi:10.5194/essd-11-1675-2019.

[47] Taylor, M., Tam, C., & Gielen, D. (2006). Energy efficiency and CO_2 emissions from the global cement industry. Korea, 50(2.2), 61-67.

[48] Panjaitan, T. W. S., Dargusch, P., Wadley, D., & Aziz, A. A. (2021). Meeting international standards of cleaner production in developing countries: Challenges and financial realities facing the Indonesian cement industry. Journal of Cleaner Production, 318, 128604. doi:10.1016/j.jclepro.2021.128604.

[49] Dinga, C. D., & Wen, Z. (2022). China's green deal: Can China's cement industry achieve carbon neutral emissions by 2060? Renewable and Sustainable Energy Reviews, 155, 111931. doi:10.1016/j.rser.2021.111931.

[50] Lim, C., Jung, E., Lee, S., Jang, C., Oh, C., & Nam Shin, K. (2020). Global Trend of Cement Production and Utilization of Circular Resources. Journal of Energy Engineering, 29(3), 57–63. doi:10.5855/ENERGY.2020.29.3.057.

[51] Mokhtar, A., & Nasooti, M. (2020). A decision support tool for cement industry to select energy efficiency measures. Energy Strategy Reviews, 28, 100458. doi:10.1016/j.esr.2020.100458.

[52] Shen, W., Cao, L., Li, Q., Zhang, W., Wang, G., & Li, C. (2015). Quantifying CO2 emissions from China's cement industry. Renewable and Sustainable Energy Reviews, 50, 1004–1012. doi:10.1016/j.rser.2015.05.031.

[53] Boisseau-Bouvier, É., & Cameron, L. (2022). Identifying Inefficient Fossil Fuel Subsidies in Canada. International Institute for Sustainable Development & Équiterre, Geneva, Switzerland.

[54] Ghalehnovi, M., Roshan, N., Taghizadeh, A., Asadi Shamsabadi, E., Ali Hadigheh, S., & de Brito, J. (2022). Production of Environmentally Friendly Concrete Incorporating Bauxite Residue and Silica Fume. Journal of Materials in Civil Engineering, 34(2), 4021423. doi:10.1061/(asce)mt.1943-5533.0004060.

[55] Billong, N., Oti, J., & Kinuthia, J. (2021). Using silica fume based activator in sustainable geopolymer binder for building application. Construction and Building Materials, 275, 122177. doi:10.1016/j.conbuildmat.2020.122177.

[56] Tak, S., Gupta, P., Kumar, A., Sofi, A., & Mei Yun, C. (2023). Effect of using silica fume as a partial replacement of cement in concrete. Materials Today: Proceedings. doi:10.1016/j.matpr.2023.04.205.

[57] Bajpai, R., Choudhary, K., Srivastava, A., Sangwan, K. S., & Singh, M. (2020). Environmental impact assessment of fly ash and silica fume based geopolymer concrete. Journal of Cleaner Production, 254, 120147. doi:10.1016/j.jclepro.2020.120147.

[58] Cong, P., & Mei, L. (2021). Using silica fume for improvement of fly ash/slag based geopolymer activated with calcium carbide residue and gypsum. Construction and Building Materials, 275, 122171. doi:10.1016/j.conbuildmat.2020.122171.

[59] Singh, L., Kumar, A., & Singh, A. (2016). Study of Partial Replacement of Cement by Silica Fume. International Journal of Advanced Research, 4(7), 104–120. doi:10.21474/ijar01/1016.

[60] Mohyiddeen, M., & Maya, T. M. (2015). Effect of silica fume on concrete containing copper slag as fine aggregate. International Journal of Research in Advent Technology, Special Issue International Conference on Technological Advancements in Structures and Construction, TASC- 15, 55-59.

[61] Luo, T., Hua, C., Liu, F., Sun, Q., Yi, Y., & Pan, X. (2022). Effect of adding solid waste silica fume as a cement paste replacement on the properties of fresh and hardened concrete. Case Studies in Construction Materials, 16, 1048. doi:10.1016/j.cscm.2022.e01048.

[62] Siddique, R. (2011). Utilization of silica fume in concrete: Review of hardened properties. Resources, Conservation and Recycling, 55(11), 923–932. doi:10.1016/j.resconrec.2011.06.012.

[63] Khan, M. I., & Siddique, R. (2011). Utilization of silica fume in concrete: Review of durability properties. Resources, Conservation and Recycling, 57, 30–35. doi:10.1016/j.resconrec.2011.09.016.

[64] Siddique, R., & Chahal, N. (2011). Use of silicon and ferrosilicon industry by-products (silica fume) in cement paste and mortar. Resources, Conservation and Recycling, 55(8), 739–744. doi:10.1016/j.resconrec.2011.03.004.

[65] Mastali, M., & Dalvand, A. (2016). Use of silica fume and recycled steel fibers in self-compacting concrete (SCC). Construction and Building Materials, 125, 196–209. doi:10.1016/j.conbuildmat.2016.08.046.

[66] Hasan-Nattaj, F., & Nematzadeh, M. (2017). The effect of forta-ferro and steel fibers on mechanical properties of high-strength concrete with and without silica fume and nano-silica. Construction and Building Materials, 137, 557–572. doi:10.1016/j.conbuildmat.2017.01.078.

[67] Fallah, S., & Nematzadeh, M. (2017). Mechanical properties and durability of high-strength concrete containing macro-polymeric and polypropylene fibers with nano-silica and silica fume. Construction and Building Materials, 132, 170–187. doi:10.1016/j.conbuildmat.2016.11.100.

[68] Wu, Z., Shi, C., & Khayat, K. H. (2016). Influence of silica fume content on microstructure development and bond to steel fiber in ultra-high strength cement-based materials (UHSC). Cement and Concrete Composites, 71, 97–109. doi:10.1016/j.cemconcomp.2016.05.005.

[69] Ju, Y., Tian, K., Liu, H., Reinhardt, H. W., & Wang, L. (2017). Experimental investigation of the effect of silica fume on the thermal spalling of reactive powder concrete. Construction and Building Materials, 155, 571–583. doi:10.1016/j.conbuildmat.2017.08.086.

[70] Soliman, N. A., & Tagnit-Hamou, A. (2017). Partial substitution of silica fume with fine glass powder in UHPC: Filling the micro gap. Construction and Building Materials, 139, 374–383. doi:10.1016/j.conbuildmat.2017.02.084.

[71] Pedro, D., de Brito, J., & Evangelista, L. (2017). Evaluation of high-performance concrete with recycled aggregates: Use of densified silica fume as cement replacement. Construction and Building Materials, 147, 803–814. doi:10.1016/j.conbuildmat.2017.05.007.

[72] Rostami, M., & Behfarnia, K. (2017). The effect of silica fume on durability of alkali activated slag concrete. Construction and Building Materials, 134, 262–268. doi:10.1016/j.conbuildmat.2016.12.072.

[73] Karthikeyan, B., & Dhinakaran, G. (2018). Influence of ultrafine TiO2 and silica fume on performance of unreinforced and fiber reinforced concrete. Construction and Building Materials, 161, 570–576. doi:10.1016/j.conbuildmat.2017.11.133.

[74] Bajja, Z., Dridi, W., Darquennes, A., Bennacer, R., Le Bescop, P., & Rahim, M. (2017). Influence of slurried silica fume on microstructure and tritiated water diffusivity of cement pastes. Construction and Building Materials, 132, 85–93. doi:10.1016/j.conbuildmat.2016.11.097.

[75] Wang, L., Zhou, S. H., Shi, Y., Tang, S. W., & Chen, E. (2017). Effect of silica fume and PVA fiber on the abrasion resistance and volume stability of concrete. Composites Part B: Engineering, 130, 28–37. doi:10.1016/j.compositesb.2017.07.058.

[76] Rastogi, A., & Paul, V. K. (2020). A critical review of the potential for fly ash utilisation in construction-specific applications in India. Environmental Research, Engineering and Management, 76(2), 65–75. doi:10.5755/J01.EREM.76.2.25166.

[77] Zhang, Y., Fan, Z., Sun, X., & Zhu, X. (2022). Utilization of surface-modified fly ash cenosphere waste as an internal curing material to intensify concrete performance. Journal of Cleaner Production, 358, 132042. doi:10.1016/j.jclepro.2022.132042.

[78] Orozco, C., Tangtermsirikul, S., Sugiyama, T., & Babel, S. (2023). Examining the endpoint impacts, challenges, and opportunities of fly ash utilization for sustainable concrete construction. Scientific Reports, 13(1), 18254. doi:10.1038/s41598-023-45632-z.

[79] Alam, J., & Akhtar, M. N. (2011). Fly ash utilization in different sectors in Indian scenario. International Journal of Emerging Trends in Engineering and Development, 1(1), 1-14.

[80] Akhtar, M. N., Khan, M. A., & Akhtar, J. (2014). Use of the falling-head method to assess permeability of fly ash based roof tiles with waste polythene fibre. International Journal of Scientific & Engineering Research, 5, 476-483.

[81] Hattamleh, O. H. A., Al-Deeky, H. H., & Akhtar, M. N. (2013). The Consequence of Particle Crushing in Engineering Properties of Granular Materials. International Journal of Geosciences, 04(07), 1055–1060. doi:10.4236/ijg.2013.47099.

[82] Adil, G., Kevern, J. T., & Mann, D. (2020). Influence of silica fume on mechanical and durability of pervious concrete. Construction and Building Materials, 247, 118453. doi:10.1016/j.conbuildmat.2020.118453.

[83] Nochaiya, T., Wongkeo, W., & Chaipanich, A. (2010). Utilization of fly ash with silica fume and properties of Portland cement-fly ash-silica fume concrete. Fuel, 89(3), 768–774. doi:10.1016/j.fuel.2009.10.003.

[84] Sasanipour, H., Aslani, F., & Taherinezhad, J. (2019). Effect of silica fume on durability of self-compacting concrete made with waste recycled concrete aggregates. Construction and Building Materials, 227, 116598. doi:10.1016/j.conbuildmat.2019.07.324.

[85] Khodabakhshian, A., Ghalehnovi, M., de Brito, J., & Asadi Shamsabadi, E. (2018). Durability performance of structural concrete containing silica fume and marble industry waste powder. Journal of Cleaner Production, 170, 42–60. doi:10.1016/j.jclepro.2017.09.116.

[86] Memon, F. A., Nuruddin, M. F., & Shafiq, N. (2013). Effect of silica fume on the fresh and hardened properties of fly ash-based self-compacting geopolymer concrete. International Journal of Minerals, Metallurgy, and Materials, 20(2), 205–213. doi:10.1007/s12613-013-0714-7.

[87] Keerio, M. A., Abbasi, S. A., Kumar, A., Bheel, N., Rehaman, K. Ur, & Tashfeen, M. (2022). Effect of Silica Fume as Cementitious Material and Waste Glass as Fine Aggregate Replacement Constituent on Selected Properties of Concrete. Silicon, 14(1), 165–176. doi:10.1007/s12633-020-00806-6.

[88] Kumar, A., Bheel, N., Ahmed, I., Rizvi, S. H., Kumar, R., & Jhatial, A. A. (2022). Effect of silica fume and fly ash as cementitious material on hardened properties and embodied carbon of roller compacted concrete. Environmental Science and Pollution Research, 29(1), 1210–1222. doi:10.1007/s11356-021-15734-0.

[89] Farahani, A., Taghaddos, H., & Shekarchi, M. (2015). Prediction of long-term chloride diffusion in silica fume concrete in a marine environment. Cement and Concrete Composites, 59, 10–17. doi:10.1016/j.cemconcomp.2015.03.006.

[90] Imam, A., Kumar, V., & Srivastava, V. (2018). Review study towards effect of Silica Fume on the fresh and hardened properties of concrete. Advances in Concrete Construction, 6(2), 145–157. doi:10.12989/acc.2018.6.2.145.

[91] Mustapha, F. A., Sulaiman, A., Mohamed, R. N., & Umara, S. A. (2019). The effect of fly ash and silica fume on self-compacting high-performance concrete. Materials Today: Proceedings, 39, 965–969. doi:10.1016/j.matpr.2020.04.493.

[92] Xu, W., Zhang, Y., & Liu, B. (2020). Influence of silica fume and low curing temperature on mechanical property of cemented paste backfill. Construction and Building Materials, 254, 119305. doi:10.1016/j.conbuildmat.2020.119305.

[93] Youm, K. S., Moon, J., Cho, J. Y., & Kim, J. J. (2016). Experimental study on strength and durability of lightweight aggregate concrete containing silica fume. Construction and Building Materials, 114, 517–527. doi:10.1016/j.conbuildmat.2016.03.165.

[94] Poornima, V., Sindhu, S., Arunachaleshwaran, A., Girish, R., Imthiyaz Ahamed, K., & Nerainjan Isai, I. (2019). Effect of silica fume and limestone powder on abrasion resistance of OPC and PPC concrete. Materials Today: Proceedings, 46, 5123–5130. doi:10.1016/j.matpr.2020.10.503.

[95] Verma, S. K., Singla, C. S., Nadda, G., & Kumar, R. (2020). Development of sustainable concrete using silica fume and stone dust. Materials Today: Proceedings, 32, 882–887. doi:10.1016/j.matpr.2020.04.364.

[96] Turk, K., Karatas, M., & Gonen, T. (2013). Effect of Fly Ash and Silica Fume on compressive strength, sorptivity and carbonation of SCC. KSCE Journal of Civil Engineering, 17(1), 202–209. doi:10.1007/s12205-013-1680-3.

[97] Khan, M., Rehman, A., & Ali, M. (2020). Efficiency of silica-fume content in plain and natural fiber reinforced concrete for concrete road. Construction and Building Materials, 244, 118382. doi:10.1016/j.conbuildmat.2020.118382.

[98] Muhit, I. B., Ahmed, S. S., Amin, M. M., & Raihan, M. T. (2013, December). Effects of silica fume and fly ash as partial replacement of cement on water permeability and strength of high performance concrete. 4th International Conference on Advances in Civil Engineering, 13-14 December, 2013, New Delhi, India.

[99] Albattat, R. A. I., Jamshidzadeh, Z., & Alasadi, A. K. R. (2020). Assessment of compressive strength and durability of silica fume-based concrete in acidic environment. Innovative Infrastructure Solutions, 5, 20. doi:10.1007/s41062-020-0269-1.

[100] Saba, A. M., Khan, A. H., Akhtar, M. N., Khan, N. A., Rahimian Koloor, S. S., Petru, M., & Radwan, N. (2021). Strength and flexural behavior of steel fiber and silica fume incorporated self-compacting concrete. Journal of Materials Research and Technology, 12, 1380–1390. doi:10.1016/j.jmrt.2021.03.066.

[101] Ismail, A. J., Younis, K. H., & Maruf, S. M. (2020). Recycled Aggregate Concrete Made with Silica Fume: Experimental Investigation. Civil Engineering and Architecture, 8(5), 1136–1143. doi:10.13189/cea.2020.080540.

[102] Jamle, S., Chouhan, P., & Verma, M. P. (2017). Effect of Silica Fume on Strength Parameters of Concrete as a Partial Substitution of Cement. International Journal for Science and Advance Research in Technology, 3(5), 968–972.

[103] Hemavathi, S., Sumil Kumaran, A., & Sindhu, R. (2020). An experimental investigation on properties of concrete by using silica fume and glass fibre as admixture. Materials Today: Proceedings, 21, 456–459. doi:10.1016/j.matpr.2019.06.558.

[104] Cheah, C. B., & Nurshafarina, J. (2019). Preliminary study on influence of silica fume on mechanical properties of no-cement mortars. IOP Conference Series: Materials Science and Engineering, 513(1), 12025. doi:10.1088/1757-899X/513/1/012025.

[105] Ajileye, F. V. (2012). Investigations on microsilica (silica fume) as partial cement replacement in concrete. Global Journal of Research In Engineering, 12(1-E).

[106] Katkhuda, H., Hanayneh, B., & Shatarat, N. (2009). Influence of silica fume on high strength lightweight concrete. International Journal of Civil and Environmental Engineering, 3(10), 407-414.

[107] Khan, M., & Ali, M. (2019). Improvement in concrete behavior with fly ash, silica-fume and coconut fibres. Construction and Building Materials, 203, 174–187. doi:10.1016/j.conbuildmat.2019.01.103.

[108] Pradhan, D., & Dutta, D. (2013). Influence of silica fume on normal concrete. International Journal of Engineering Research and Applications, 3(5), 79-82.

[109] Okoye, F. N., Durgaprasad, J., & Singh, N. B. (2016). Effect of silica fume on the mechanical properties of fly ash based-geopolymer concrete. Ceramics International, 42(2), 3000–3006. doi:10.1016/j.ceramint.2015.10.084.

[110] Ahmad, O. A. (2017). Production of High-Performance Silica Fume Concrete. American Journal of Applied Sciences, 14(11), 1031–1038. doi:10.3844/ajassp.2017.1031.1038.

[111] Liu, H., Elchalakani, M., Karrech, A., Yehia, S., & Yang, B. (2021). High strength flowable lightweight concrete incorporating low C3A cement, silica fume, stalite and macro-polyfelin polymer fibres. Construction and Building Materials, 281, 122410. doi:10.1016/j.conbuildmat.2021.122410.

[112] Smarzewski, P. (2019). Influence of silica fume on mechanical and fracture properties of high-performance concrete. Procedia Structural Integrity, 17, 5–12. doi:10.1016/j.prostr.2019.08.002.

[113] Wang, J., Xie, J., He, J., Sun, M., Yang, J., & Li, L. (2020). Combined use of silica fume and steel fibre to improve fracture properties of recycled aggregate concrete exposed to elevated temperature. Journal of Material Cycles and Waste Management, 22(3), 862–877. doi:10.1007/s10163-020-00990-y.

[114] Valipour, M., Pargar, F., Shekarchi, M., & Khani, S. (2013). Comparing a natural pozzolan, zeolite, to metakaolin and silica fume in terms of their effect on the durability characteristics of concrete: A laboratory study. Construction and Building Materials, 41, 879–888. doi:10.1016/j.conbuildmat.2012.11.054.

[115] Bahadori, H., & Hosseini, P. (2012). Reduction of cement consumption by the aid of silica nano-particles (investigation on concrete properties). Journal of Civil Engineering and Management, 18(3), 416–425. doi:10.3846/13923730.2012.698912.

[116] Mohan, A., & Mini, K. M. (2018). Strength Studies of SCC Incorporating Silica Fume and Ultra-Fine GGBS. Materials Today: Proceedings, 5(11), 23752–23758. doi:10.1016/j.matpr.2018.10.166.

[117] Mehta, A., & Ashish, D. K. (2020). Silica fume and waste glass in cement concrete production: A review. Journal of Building Engineering, 29, 100888. doi:10.1016/j.jobe.2019.100888.

[118] Chu, S. H., & Kwan, A. K. H. (2019). Co-addition of metakaolin and silica fume in mortar: effects and advantages. Construction and Building Materials, 197, 716–724. doi:10.1016/j.conbuildmat.2018.11.244.

[119] Motahari Karein, S. M., Ramezanianpour, A. A., Ebadi, T., Isapour, S., & Karakouzian, M. (2017). A new approach for application of silica fume in concrete: Wet granulation. Construction and Building Materials, 157, 573–581. doi:10.1016/j.conbuildmat.2017.09.132.

[120] Demirel, B., & Keleştemur, O. (2010). Effect of elevated temperature on the mechanical properties of concrete produced with finely ground pumice and silica fume. Fire Safety Journal, 45(6–8), 385–391. doi:10.1016/j.firesaf.2010.08.002.

[121] Ahmad, S., Umar, A., Masood, A., & Nayeem, M. (2019). Performance of self-compacting concrete at room and after elevated temperature incorporating Silica fume. Advances in Concrete Construction, 7(1), 31–37. doi:10.12989/acc.2019.7.1.031.

[122] Mahalakshmi, S. H. V., & Khed, V. C. (2020). Experimental study on M-sand in self-compacting concrete with and without silica fume. Materials Today: Proceedings, 27, 1061–1065. doi:10.1016/j.matpr.2020.01.432.

[123] Siddique, R., Jameel, A., Singh, M., Barnat-Hunek, D., Kunal, Aït-Mokhtar, A., Belarbi, R., & Rajor, A. (2017). Effect of bacteria on strength, permeation characteristics and micro-structure of silica fume concrete. Construction and Building Materials, 142, 92–100. doi:10.1016/j.conbuildmat.2017.03.057.

[124] Salman Rais, M., & Ahmad Khan, R. (2021). Effect of biomineralization technique on the strength and durability characteristics of recycled aggregate concrete. Construction and Building Materials, 290, 123280. doi:10.1016/j.conbuildmat.2021.123280.