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A Review on The Impact of Industrial by-products as Cementitious Materials on the behavior of concrete

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Abstract

The paper gives a systematic literature review about the use of industrial by-products, fly ash, ground granulated blast furnace slag (GGBFS), silica fume, and waste glass powder as supplementary cementitious materials (SCMs) in concrete. Which identifies, screens, and critically synthesizes over 50 peer-reviewed studies published between 2000 and 2025. The paper provides a thorough analysis and discussion of the chemical and physical properties, pozzolanic and hydraulic activities and effects on fresh and hardened concrete, workability, setting time, strength development, and long-term durability. Moreover, it discusses the environmental and financial effects, including CO_2 emissions, landfill waste diversion, cost efficiency, and conservation of resources. The findings indicate that fly ash (15-30% replacement) strengthens in the long term and provides sulfate resistance; silica fume (5-10%) strengthens early age strength and impermeability; GGBFS (30-50%) makes it stronger in adverse environments; and waste glass powder reduces alkali-silica reactivity and encourages waste application. Altogether, the analyzed literature suggests that SCMs have the potential to reduce CO_2 emissions from cement production by up to 50 percent and contribute to a circular economy.

Keywords: Cementitious, Sustainable construction, Waste utilization, Carbon footprint reduction, Alternative binders.

1. Introduction

Concrete has always been the mainstay of worldwide construction, but its environmental effects, specifically the high CO2 emissions of cement, are immense and take up approximately 7-8% of emissions worldwide [1]. This has spurred interest in the implementation of sustainable construction methods such as the use of industrial by-products as supplementary cementitious materials (SCMs). When used as partial cement replacements, these materials can reduce environmental impact without compromising concrete quality.

By-products of the industrial sector, including fly ash, slag, and silica fume, have been heavily researched in their pozzolanic reactivity in the form of hydraulic reactivity; this lends to the performance of concrete. The construction of these materials is in line with the need worldwide to adopt a sustainable stance in the construction industry by limiting landfills and preserving natural resources. The environmental issues affiliated with the production of concrete have triggered a move to conduct massive research to find out viable ways in which concrete can be produced in a sustainable manner without impairing structural performance. There is a high rate of CO_2 emitted during cement production as well as the extensive consumption of natural resources during the process, such as limestone and fossil fuels, which leads to ecological degradation [2]. The construction industry can also rely on industrial by-products such as SCMs to reduce its carbon impact to great extents and contribute to a closed-loop economy by using waste material constructively as renewed resources.

Silica and alumina, which are obtained in fly ash produced during combustion of coal in thermal power plants, are also considered to augment the pozzolanic activity of fly ash, thus augmenting the long-term strength and durability of concrete [3]. On the same note, ground granulated blast furnace slag (GGBFS), which is a by-product of the steel industry, has latent hydraulic properties, hence enhancing better sulfate resistance and lowering permeability, making it important when providing longer-lasting durability in aggressive environments [4]. Because of its high pozzolanic reactivity and a very fine particle size, silica fume, which is a by-product of silicon metal and ferrosilicon alloy industries, enhances the interfacial transition zone in concrete and boosts its mechanical performance [5].

There will also be an advantage of low heat of hydration when these SCMs are used to help reduce thermal cracking of mass concrete, which is highly advantageous to large-scale projects like dams and foundations. The environmental benefits of the activities go past the reduction of CO_2 given the fact that these activities will minimize the amount of industrial waste that ends up in the landfill and hence mitigate the risk of contamination of the environment and the costs of disposal. Moreover, the use of SCMs may lead to enhanced workability and pumpability of fresh concrete such that the former can be easily placed and compacted, thus minimizing segregation and bleeding when adequately formulated [6].

New material science and nanotechnology are also helping in improving the reactivity of these by-products, increasing their range of use in high-performance and ultra-high-performance concrete designs. More significantly, computation of the properties of concrete with SCMs under alternative curing and other environmental exposures has depicted good strength and capability not to trade durability at the expense of attaining sustainability objectives [7]. Utilization of the industrial by-products contributes to the development of the low-carbon infrastructure and corresponds to the Sustainable Development Goals (SDGs), specifically, Goal 9 (Industry, Innovation, and Infrastructure) and Goal 13 (Climate Action).

Besides the environmental and technical advantages, economic advantages are also witnessed where there is a possibility of reducing the cost of cement, especially in areas where by-products are found locally and need minimal treatment. Nevertheless, quality control of by-products is fundamental considering that the chemical content as well as the fineness of this by-product varies, and this could influence the hydration rate and the overall concrete performance goals [8].

Thus, this review will describe an extensive account of the most widely utilized industrial by-products found in cementitious materials, especially considering their impact on the properties of fresh and hardened concrete, their durability, and their general way of being sustainable. It outlines the existing state of the art and focuses on the recent innovations in the optimization of the replacement levels, the mix-and-match hybrid SCMs, and performance-enhancing predictive modeling. The result can be to facilitate a quicker and wider adoption of these sustainable materials in various construction settings in every part of the globe.

1.1 Research Questions

The purpose of this review is to provide answers to the following research questions:

1. What are the effects of using industrial by-products as SCCMs on the fresh and hardened characteristics of concrete?
2. Different SCMs have varying effects on the durability of concrete when exposed to various environmental conditions?
3. What are the optimum replacement levels reported for the most commonly used industrial by-products?

1.2 Novelty and Scope of the Review

Unlike many previous studies that focused on specified supplementary cementitious material, the present review offers a general overview of the most commonly used industrial by-products used in cementitious systems. It looks at how much it affects the properties of fresh and hardened concrete, durability and sustainability issues. In addition, the review provides an overview of the latest research on replacement rates and the use of various industrial by-products to make sustainable concrete.

Hence, this review presents a detailed overview of the commonly used industrial by-products in cementitious materials, their impact on the performance of concrete and their role in sustainable construction.

2. Methodology of Literature Review

The systematic literature review (SLR) method was used in this research work, where the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were adhered to, providing transparency, consistency, and reproducibility of the entire review process. The process was divided into four key steps, including identification, screening, eligibility, and inclusion. During the identification phase, a full search was done in key academic databases, such as Scopus, ScienceDirect, SpringerLink, and Google Scholar. The first search resulted in a total of 340 records found in databases, with 70 of the same found elsewhere. Having eliminated the duplicates, 260 distinct records were left to be analyzed. At the screening stage, the titles and abstracts of the retrieved articles were reviewed to rule out irrelevant or non-English articles and those that were not concerned with cementitious materials. As a result, 77 records were filtered out, and 190 studies were subjected to screenings. During the eligibility phase, 113 articles in their entirety were evaluated using certain inclusion criteria, which stipulated that the articles should be peer-reviewed articles that contain either quantitative or qualitative data relating to one or more of the following aspects: technical, environmental, or economic performance of supplementary cementitious materials (SCMs). Articles that were only descriptive reviews or not connected with the real use of SCMs were eliminated, and 58 articles were eliminated at this point. Lastly, 55 studies were of high quality and passed all the inclusion criteria and were included in the final review. These works were examined to obtain information about the kind and percentage of SCMs applied, their impact on fresh and hardened concrete qualities, and their impact on longevity, ecological impact, and cost-efficiency. The retrieved data were then synthesized together in an organized fashion to illustrate dominant trends, contradictions, and research gaps that existed on the topic of using industrial by-products as an addition to cementitious materials. The overall process of identification, screening, eligibility, and inclusion is summarized in figure (1).

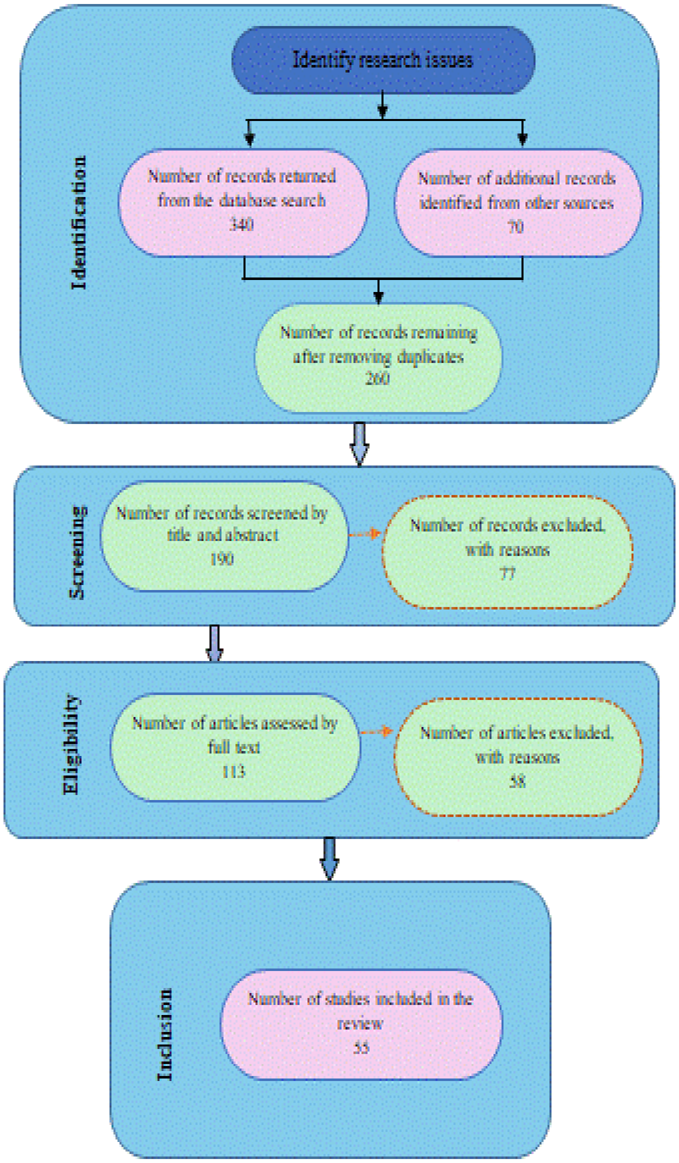

Figure 1. PRISMA diagram that illustrates the inclusion and exclusion process of the different papers in each of the review stages to identify the pertinent literature in the online databases.

3. Classification of Industrial By-products

Concrete by-products may be grouped according to chemical and physical characteristics of promoting hydration and strength growth. Calcium hydroxide alkalinity reacts with fly ash, silica fume, rice husk ash, and other pozzolanic by-products, forming extra C-S-H that enhances durability and aging strength [3] [9]. Dormant hydraulic-binding materials like GGBFS will react with water in the existence of activators to produce hydration materials, producing a higher sulfate resistance and durability [10]. Other high-pH residuals such as CKD and red mud have the potential but should be carefully tended because of being variable and environmentally sensitive. New materials, like waste glass powder and steel slag, are also under consideration as aggregate replacements or pozzolanic contributions with the aim of keeping the environmental impact low but keeping the mechanical performance high. Each product has different fineness, reactivity, and mineral composition, which affects its appropriateness and the amount used in concrete, as shown in Table 1.

Table 1: typical chemical and physical properties of major SCMs.

SCM	Chemical Composition (main oxides,%)	Specific Gravity	Particle Size	Key Characteristics
Fly ash	Sio_2 40-60, $Al_2o_3$20-30,cao 5-10	2.1-2.6	1-100 µm	Pozzolanic, improves workability, lower early strength
GGBFS	Cao 30-40, Sio_2 30-40, Al_2O_3 10-15, MgO 8-10	2.8-3	1-45µm	Latent hydraulic, enhances durability, sulfate resistance
Silica Fume (SF)	SiO_2 >85-95	2.2	<1µm	Highly pozzolanic, improves strength and ITZ
Waste Glass Powder (WGP)	SiO_2 60-75, CaO 8-12, Na_2O 12-15	2.5	<75µm	Reduces ASR, refines pore structure

3.1. Pozzolanic By-products - Fly Ash:

Fly ash (FA) and silica fume (SF) are common pozzolanic by-products, which have been highly investigated as cementitious materials to improve the performance and sustainability of a cement mix. FA falls under ASTM C618 Class F and Class C categorizations [11], under which Class F often has varying substances in comparison to Class C, serving as they are highly pozzolanic and possess low content in calcium and have a higher composition of silica-alumina, whereas Class C has high contents of CaO that contribute to its self-cement containment [3]. The pozzolanic reaction of the FA with the calcium hydroxide (CH) forms more calcium-silicate-hydrate (C-S-H), which alleviates the long-term strength, decreases the heating of hydration, and increases the sulfate resistance [12].

3.2. Latent Hydraulic By-products—Ground Granulated Blast Furnace Slag:

Many research papers have been conducted regarding the characterization of ground granulated blast furnace slag (GGBFS) in cementitious products to improve durability and sustainable research. Song et al. (2006), in their survey regarding the corrosion resistance of concrete that contained GGBFS, recorded that concrete became more resistant to chloride penetration and that rates of corrosion were slowed by enhanced formation of a much denser microstructure with C-S-H gels. [10] Sulfate resistance of the GGBFS-blended concrete improves as greater quantities of the slag are used in the composition, resulting in a significant reduction of expansion and corrosion of the concrete surface. This enhancement plays an important role in the durability of the concrete over long-term sulfate-rich conditions [3]. The use of supplementary cementitious material, such as GGBFS, was reviewed by Juenger and Siddique (2015) [13], and its use and potential to be adopted to reduce the carbon footprint of the cement industry with the mechanical and durability performance at least as good as Portland cement-based concrete, and possibly even better [14]. examined the mechanical and microstructural characteristics of GGBFS concrete and reported that substitution with GGBFS resulted in a higher compressive strength, low permeability, and pore structure resolution, which plays a significant role in the sustainability and durability of concrete in harsh areas.

3.3. Alkaline or High pH By-products—Cement Kiln Dust (CKD):

The past few years have seen some research on alkaline industrial wastes, namely cement kiln dust (CKD) and red mud, to be utilized in cementitious systems to improve sustainability and performance as well as handle wastes. Lee et al. (2024) [15] tested concrete containing cement partly replaced by CKD, reporting that optimal replacement rates can support early but not later strength gain because of the faster reaction of CKD with water and final product formation without emissions of CO_2, which can be elevated when higher substitution rates are used, as the probability of efflorescence can also rise. The geopolymerization of red mud blended with fly ash showed that the alkali activation process can take advantage of red mud, producing high compressive strength in binders and the low leaching of heavy metals that is environmentally friendly. [16]

3.4. Waste Glass Powder:

The use of pozzolanic and industrial by-products, including waste glass powder, steel slag, and phosphogypsum, as cementitious materials has been investigated in recent studies as a way of making cementitious materials more sustainable in terms of cost and facilities impacted (environment) and subsequent improvements in mechanical and durability properties. Islam et al. (2017) [17] investigated the efficacy of waste glass powder as a partial substitute for cement, which showed enhanced compressive strength and lesser alkali-silica reactivity because of its pozzolanic characteristic and refinement of pore structure. Pushpakumara et al. (2023) [18] assessed the steel slag as a partially substituted fine and coarse aggregate material in concrete with improved toughness and better abrasion resistance, in addition to satisfactory mechanical properties, and made good use of steel industry waste materials, which further improves the concrete structure. In other research, Ha-Minh et al. (2020) [19] evaluated the feasibility of partially using phosphogypsum in blended cement and found that it could be used to improve early-age strength but with stringent control, as radioactivity and leaching of heavy metals are major concerns with phosphogypsum; thus, it should be treated prior to any usage. Also, they investigated the joint application of waste glass powder and steel slag in alkali-based binders and found synergistic effects, as the use of this combination improves compressive strength, decreases CO_2 emissions, and develops a more favorable concrete mixture sustainability profile. [20]

4. Effect on Fresh Properties of Concrete

4.1. Workability

The majority of studies have shown that fly ash increases workability because it has spherical particles[21], and silica fume decreases workability because it has a high specific surface area[9]. GGBFS, on the other hand, offers a moderate improvement in cohesion without making slump very high[13]. These variations are primarily due to different ratios of replacement, different fineness of the particles and different proportions of water to binder, reflecting the variability in the performance of different SCM mixtures, not the type of SCM.

4.2. Setting Time

Industrial by-products in use as supplementary cementitious materials (SCMs) are a significant consideration for the setting of concrete because of their chemical reactivity and physical qualities. Fly ash is a general delaying admixture due to its low early-stage reactivity and necessitates the availability of calcium hydroxide at the time of cement hydration to initiate its pozzolanic reactions, thus bestowing additional working and finishing time of concrete [21]. Silica fume, conversely, has a strong potential to decrease the setting time, as it has a very fine particle size and intense surface area, which offers more nucleation sites to the formation of calcium silicate hydrate (C-S-H) that causes quick stiffening of the mix [22]. In most cases, GGBFS slightly extends the setting time, as it has latent hydraulic properties that hydrate more slowly than ordinary Portland cement, leading to a slightly slower initial and final set, never affecting performance adversely when used at acceptable levels of replacement [12].

4.3. Heat of Hydration

Use of industrial by-products as supplementary cementitious materials is also known to have profound effects on heat of hydration in concrete with respect to their degrees of chemical reactivity and replacement effects. Fly ash tends to decrease the heat of hydration due to its low initial reactivities, which not only delays the overall hydration process but also decreases temperature increase in concrete, which is useful when having to address mass concrete, where limitations may be imposed by thermal cracking [21]. In a similar manner, ground granulated blast furnace slag (GGBFS) reduces the heat of hydration because it hydrates less quickly than Portland cement, hence leading to a slow rise of the peak temperature in early curing [23], [24]. Conversely, silica fume can modestly raise the level of heat during the initial stages because of the high surface area and consequently pozzolanic reactivity, which can hasten cement hydration when administered in low doses, albeit the overall heat generation is lower than that of the same amount of cement with no silica fume added [9].

5. Effect on Hardened Properties

5.1. Compressive Strength

Compressive strength development of concrete depends significantly on the by-product type, replacement level, and curing conditions when they are used as supplementary cementitious materials (SCMs). Low early-age compressive strength is typically achieved with fly ash because of the low pozzolanic reactivity, whereas strength increases at intermediate and later stages as the pozzolanic reaction progresses by depleting calcium hydroxide and forming further calcium silicate hydrate (C-S-H), resulting in a denser microstructure [21]. Ground granulated blast furnace slag (GGBFS), similarly to plain cement concrete, has a comparable effect of decreasing early strength and will improve long-term compressive strength, especially under optimal curing, because they have latent hydraulic characteristics and because they may improve the pore structure [24]. [25]. Conversely, silica fume contributes massively to early and later-age compressive strength because it is highly pozzolanic and has ultra-fine particles capable of filling the spaces between cement grains and reducing porosity, which in turn advances the hydration mechanism with designer super plasticizers. [9].

5.2. Flexural and Tensile Strength

The addition of industrial by-products as supplementary cementitious materials (SCMs) has a significant influence on the flexural strength and tensile strength of concrete due to improvement in microstructure and inhibition of the crack network. The incorporation of silica fume in the geopolymer concrete contributes to significantly enhancing flexural and tensile strength at early and later ages, as the silica fume has an ultra-fine particle size and high pozzolanic reactivity that helps refine the pore structure and improve the paste-aggregate bond [26]. Just as discovered, using silica fume and fly ash in reactive powder concrete was found to improve the flexural strength by up to 7% and the tensile strength by up to 19% relative to control mixes, with silica fume and fly ash delivering the initial reactivity of the concrete and long-lasting strength growth over time as the pozzolanic process continued [27]. Using fly ash and GGBFS in degradable concrete mixtures enhances eco-friendliness, as well as comparable or superior flexural and All these results point to the fact that even though silica fume is associated with the most evident positive short-term effects on flexural and tensile properties, the combination of fly ash and GGBFS shows a sustainable route to developing superior concrete performance within structural uses in the long term [28].

5.3. Modulus of Elasticity

Industrial by-products, fly ash, silica fume, and ground granulated blast furnace slag (GGBFS), used as separate cementitious materials (SCMs), also affect the modulus of elasticity of concrete through altering its microstructure properties and stiffness. Recent research has shown that fly ash is likely to have a slight decreasing early-age modulus of elasticity because it has slower hydration and pozzolanic reactions, yet at later ages it can be equal or even superior, as the microstructure becomes denser [29]. Due to its fine particle size, pozzolanic reactivity, and high level, silica fume increases the modulus of elasticity more effectively because of the decrease in porosity and enhancement of the bond strength in the cement matrix [30]. Equally, lowered modulus of elasticity during early ages of curing is also increased through contributing to a denser and more homogeneous microstructure through latent hydraulic quality and the filler effect of GGBFS [31]. These results prove that despite the initial potential of SCMs to increase or decrease the stiffness of concrete, the overall effect of these materials, in the long run, is expected to yield better or similar moduli of elasticity, which is advantageous in terms of providing a harmonized fusion between sustainability and the mechanical performance of concrete.

5.4. Density

Density of concrete is influenced by the incorporation of industrial by-products like fly ash, silica fume, and ground granulated blast furnace slag (GGBFS) as supplementary cementitious materials (SCMs), as they alter the microstructure and the efficiency of the packing within the concrete. Modern investigations reveal that fly ash has a rounded particle structure and a specific weight that is slightly lower than that of cement, which, as a result, can help to make concrete mixtures less dense to a mild extent [32]. Silica fumes, on the other hand, could work well due to their ultra-fine particles, which strengthen the packing of the particles and occupy the spaces in the cement matrix, thus making the concrete denser and having higher density values [33]. GGBFS similarly plays a role in enhancing the packing of the particles and hence lowers porosity, and the pore-enhanced bulk density of concrete may rise as hydration and hardening of the slag occur with time [34].

6. Durability Performance

The use of industrial by-products fly ash, silica fume, and ground granulated blast furnace slag (GGBFS) as supplementary cementitious materials (SCMs) is known to strongly improve the durability behavior of concrete by improving its microstructure and lowering permeability. By pozzolanic reaction, fly ash eliminates calcium hydroxide created during cement hydration and generates more calcium silicate hydrate (C-S-H) that condenses cement structure and reduces pore connectivity. It results in higher resistance to detrimental agents, including chloride ions, sulfates, and alkali-silica reaction [27], [35]. Further, cement integration of fly ash has been associated with lower heat of hydration, reducing the risk of thermal cracking in mass concrete. Due to this credit, increased durability in the concrete is also achieved. Silica fume has an ultra-fine size and very high surface area that simultaneously serves as a micro-filler and a highly active pozzolan, which fills micro-voids and accelerates hydration reactions. This leads to a very weakly permeable solid matrix that has increased freeze-thaw resistance, resistance to chemical attacks, and abrasion. [36] Also, silica fume enhances the interfacial transition zone between aggregate and cement paste, which further enhances the durability properties. Latent hydraulic activity is achieved by ground granulated blast furnace slag (GGBFS), which, during concrete curing, creates a more homogeneous and denser microstructure that adds to the durability. GGBFS is remarkably effective in its ability to inhibit permeability, raise resistance to sulfates, and enhance concrete durability in the harsh marine environments. [36], [37] .

7. Environmental and Economic Aspects

7.1. CO_2 Emissions Reduction

Supplementary cementitious materials (SCM) like fly ash, silica fume, and ground granulated blast furnace slag (GGBFS) are used as industrial by-products in concrete components to minimize CO_2 emissions related to this product. As Portland cement production is one of the largest emitters of CO_2 emissions globally because of the calcining of limestone and other energy-intensive means, partial replacement of cement with SCMs considerably reduces the carbon footprint of concrete [38], [39]. Fly ash, a coal combustion by-product, does not only displace landfill waste but also displaces concrete production, thus cutting down on CO_2 emissions in direct proportion to its substitute volume [40]. Silica fume, a byproduct of silicon and ferrosilicon alloy manufacture and similar to silica fume in that it replaces part of the cement, has a similar benefit but is less readily available. The use of GGBFS is a by-product of the iron-making process, which provides significant environmental advantages due to reduced energy consumption and CO_2 emissions and increased concrete performance [41]. Recent life cycle analyses (LCAs) have shown how these SCMs can lower the embodied carbon of concrete by as much as 30-50%, according to the percent of concrete replaced and mix design [42]. This two-fold benefit that increases the durability and sustainability of concrete corresponds to international objectives of carbon-neutral construction and contributes to the transition towards greener infrastructure building.

7.2. Waste Utilization

By utilizing industrial by-products, which is very crucial in effective waste utilization, considerable amounts of industrial waste are utilized to develop into useful building materials. As mentioned in the previous section regarding CO_2 reduction, this approach also addresses waste management. For instance, fly ash utilization not only reduces emissions but also diverts significant waste from landfills [43]. Likewise, GGBFS reuses a large industrial byproduct, avoiding the use of landfills and making industrial symbiosis more sustainable [44], [45]. Silica fume, too, helps reduce the amount of waste, as it is a used by-product that instead would have to be thrown away. Utilization of these SCMs not only solves the problem of industrial waste collection but also promotes the circular economy, through which waste streams are added to the concrete production cycle, minimizing environmental impact and maximizing conservation of natural resources [46], [47]. Recent studies affirm that the use of SCMs in cementitious material is a viable option for waste management in the construction industry towards sustainable development.

7.3. Cost Efficiency

Industrial by-products help the process of concrete production to be more cost-effective. The use of SCMs also means a direct decrease in the cost of materials since SCMs in part replace Portland cement, the most costly constituent in concrete since it is an energy-intensive product [48]. GGBFS and fly ash can be purchased at lower costs, as they are industrial waste products, with the former lowering the total cost of the binder and ensuring at least a comparable concrete performance ([49]. It is noted that silica fume may be commoditized at a relatively higher cost per ton compared to fly ash and GGBFS but used in small quantities to add strength and lasting resistant properties that result in less cement allotment and an extended service life of structures, resulting in cost savings over the life of the structure [50]. Besides, using SCMs will minimize maintenance and repair owing to enhanced strength, and this will further save on the cost over the concrete structure life cycle [51]. Therefore, the use of SCM not only complies with the aspects of sustainability but also has economic advantages through cost reduction on the cost of raw materials and the cost of long-term operations in concrete constructions.

7.4. Resource Conservation

Utilization of by-products in industries helps a lot in saving resources in the construction sector. SCMs help to reach such a goal, as they partially substitute Portland cement, a material whose manufacture requires enormous amounts of natural resources: limestone, clay, etc. [52]. In addition to the environmental benefits discussed earlier, these SCMs contribute significantly to resource conservation by reducing the demand for virgin materials [53]. Silica fume, which is produced as a by-product of silicon metal production, also promotes resource efficiency because it makes use of a waste product. Furthermore, by using such SCMs, the production of the raw material needed to be extracted and processed drops, which resulted in a decrease in the environmental degradation and disturbances of the habitat [54]. Through a recent sustainability evaluation, it has been confirmed that SCM inclusion is one aspect that not only reduces the natural resource exhaustion but also contributes to the sustainable development goals (SDGs), considering its capability to deliver eco-friendly construction works and to curb the environmental impact on the concrete lifecycle. [55]

8. Overview of SCMs and Their Influence on the Properties of Concrete

According to the literature reviewed, the general effect of different supplementary cementitious materials (SCMs) on the concrete performance could be summarized based on their recommended replacement rates, primary advantages, and possible disadvantages. Table (2) gives a brief description of the most prevalent SCMs, the ideal replacement ranges found in the literature, and their results in the fresh and hardened concrete properties. This synthesis addresses the patterns of consistency that can be observed throughout the studies and the practical constraints that are to be considered in real practice.

Table 2. Summary of SCM, Recommended Replacement Level, and Effect on Concrete Properties

SCM type	Typical replacement%	Effect on strength	Effect on durability	Environmental/economic impact
Fly Ash (FA)	15-30%	Lower early strength, higher long term strength	Improved sulfate and chloride resistance	Reduces CO2 emissions, utilizes waste
GGBFS	30-50%	Moderate early strength, high long-term strength	High sulfate resistance, low permeability	Lowers embodied energy, cost saving
Silica Fume (SF)	5-10%	Significant early and later strength gain	High resistance to ASR, chloride ingress	Limited availability, higher cost but long term saving
Waste Glass Powder (WGP)	10-20%	Comparable or slightly higher compressive strength	Reduces Alkali- silica reactivity	utilizes waste glass, reduces landfill

9. Conclusions

The overall observation of this review is the great potential in the application of industrial by-products in the concrete industry as supplementary cementitious material (SCM). The major findings based on this study are as follows:

1-Technical Performance:

The mechanical and durability properties of concrete are enhanced by partially replacing cement with industrial by-products like fly ash, silica fume, ground granulated blast furnace slag (GGBFS), and waste glass powder. Although materials such as fly ash and GGBFS can cause a decrease in early strength, much better long-term strength and durability are achieved. The ultra-fine particle size and high reactivity of silica fume make it highly reactive and can show significant gains in early and later-age compressive, tensile, and flexural strength.

2- Fresh Concrete Properties:

The spherical particles make fly ash easier to work with and pump. The workability is adversely affected by silica fume except when high-range water reducers are incorporated; it enhances cohesiveness and decreases segregation. Depending on the type of SCM in use, setting time can be delayed or speeded up, fly ash generally increasing it and silica fume decreasing it.

3-Durability Enhancement:

The result of the application of SCMs includes decreased permeability, better chloride and sulfate attack resistance, and superior performance in hostile environments.

4-Environmental Sustainability:

The use of industrial by-products as a substitute for cement has a very big impact on the reduction of the CO_2 emissions in place of the Portland cement production. Employment of SCMs is favorable to the use of waste, and it correlates with the principles of circular economy and sustainable development goals (SDGs).

5-Economic and Resource Efficiency:

The total production cost of concrete can be lowered using SCMs with the availability of by-products in immediate surroundings. These materials lead to conservation of resources since they help save on raw virgin materials such as limestone and clay.To summarize, the use of industrial by-products as components of cementitious systems does not only guarantee improved performance and strength of concrete but also promotes sustainability and economic viability of the environment. Future studies are expected to have optimal mix designs and circumvent the inconsistency in the properties of SCM to have wider usage worldwide.

Based on the reviewed studies, industrial by-products are seen to effectively be used as a supplementary cementitious material and reduce the consumption of cement and environmental impact of concrete production. The major benefits of fly ash are in the area of long-term durability and sustainability, and of GGBFS, although it is not as effective as fly ash in this regard, it still offers substantial improvements, especially with regards to permeability, due to its fine particle size and high pozzolanic activity; silica fume is especially effective in the area of mechanical properties and permeability reduction.

The replacement level, chemical composition, fineness and curing conditions strongly affect the performance of SCM. Hence it is difficult to compare the results of different studies due to variations in experimental methods and material properties.

While great efforts have been made in the application of industrial waste in concrete, the need for further research to create a comprehensive set of guidelines for the most effective replacement levels and to assess the durability over time of the concrete in various environments. Further research is also required to evaluate the performance of using more than one SCM and their practical application on large scale construction projects.

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مراجعة حول تأثير المنتجات الثانوية الصناعية كمواد إسمنتية على سلوك الخرسانة

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الخلاصة

تقدم هذه الورقة مراجعة منهجية للأدبيات العلمية المتعلقة باستخدام المنتجات الثانوية الصناعية، مثل الرماد المتطاير، وخبث الأفران الحبيبي المطحون **(GGBFS)**، ودخان السيليكا، ومسحوق الزجاج المهدور، بوصفها مواد إسمنتية تكميلية **(SCMs)** في الخرسانة. وتشمل المراجعة تحديد وفرز وتحليل نقدي لأكثر من 50 دراسة محكّمة منشورة خلال المدة من 2000 إلى 2025.

تقدم الدراسة تحليلاً ومناقشة شاملة للخصائص الكيميائية والفيزيائية لهذه المواد، ونشاطها البوزولاني والهيدروليكي، وتأثيرها في خواص الخرسانة الطرية والمتصلدة، وقابلية التشغيل، وزمن الشك، وتطور المقاومة، والمتانة طويلة الأمد. كما تناقش التأثيرات البيئية والاقتصادية، بما في ذلك انبعاثات ثاني أكسيد الكربون، وتحويل المخلفات عن مواقع الطمر، وكفاءة الكلفة، والحفاظ على الموارد الطبيعية.

تشير نتائج الدراسات التي تمت مراجعتها إلى أن الرماد المتطاير يعزز المقاومة في الأعمار المتأخرة ويوفر مقاومة أفضل للكبريتات عند نسب استبدال تتراوح بين 15–30% ، في حين أن دخان السيليكا يحسن مقاومة الخرسانة في الأعمار المبكرة ويقلل نفاذيتها عند نسب استبدال 5–10%. أما خبث الأفران الحبيبي المطحون فيحسن أداء الخرسانة في البيئات القاسية عند نسب استبدال تتراوح بين 30–50% ، بينما يساهم مسحوق الزجاج المهدور في تقليل تفاعل القلويات السيليكا وتشجيع إعادة استخدام المخلفات. وبصورة عامة، تشير الأدبيات التي تم تحليلها إلى أن المواد الإسمنتية التكميلية تمتلك القدرة على خفض انبعاثات ثاني أكسيد الكربون الناتجة من إنتاج الأسمنت بما يصل إلى 50%، فضلاً عن دعم الاقتصاد الدائري.

الكلمات الدالة: المواد الإسمنتية، البناء المستدام، استخدام المخلفات، خفض البصمة الكربونية، المواد الرابطة البديلة.