Parametric Evaluation of Supplementary Cementitious Materials Effectiveness in Improving Concrete Durability

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Abstract: In this study, a complete parametric evaluation is carried out to measure the effectiveness of Supplementary Cementitious Materials (SCMs) in the durability and sustainability of concrete. Three SCMs are analysed: fly ash, ground granulated blast-furnace slag (GGBS), and silica fume. The concrete structure gets affected by various deterioration mechanisms, including chloride ingress, sulphate attack, alkali-silica reaction (ASR), carbonation, freeze-thaw cycles, and chemical abrasion, all these factors adversely affecting long-term performance. Modern SCMs help counter these challenges by promoting pore structure refinement leading to a decrease in porosity permeability as well as chemical and physical attack resistance. Fly ash resist sulphate attacks and makes concrete strong at an age under consideration. GGBS helps in the reduced heat of hydration and increased resistance to chloride and sulphate penetration, while silica fume increases strength at early ages and reduces permeability owing to its ultrafine particles with high pozzolanic reactivity. The study also stresses the important parameters influencing the durability performance levels, that are: replacement levels, water-to-binder ratio, curing methods, and particle size. Through various standard durability tests and indicators, this research reveals that SCMs enhanced the performance and durability of concrete in aggressive environments: On preserving the environment, it has also been claimed in the study that SCMs help lower carbon emissions and utilize industrial by-products, keeping concrete technology within the spirit of the sustainability criteria and current construction demand.

Keywords: Concrete durability, Supplementary Cementitious Materials, fly ash, ground granulated blast-furnace slag (GGBS), silica fumes, alkali-silica reaction (ASR), carbonation, freeze-thaw resistance, and acid and abrasion resistance.

I. INTRODUCTION

Although concrete has great strength as a construction material, its long-term heuristic study revealed that it is suffered with numerous deterioration mechanisms. Such environmental exposure, chemical attack, or physical stresses significantly influence its performance from the long term. Among many of the possible causes of deterioration are penetration of the chloride ions leading to corrosion of the reinforcing steel, sulphate attack which causes expansion and cracking, and continued effects of the freeze-thaw cycles that generate internal stresses, then spalling [1]. Carbonation, which is a kind of reaction between carbon dioxide and calcium hydroxide in the concrete, will further lower down the pH and accelerate reinforcement corrosion. These mechanisms undermine the integrity of structures, their serviceability, and lifespan [2]. The mix design is usually bad, poor curing, or along with higher water-to-cement ratios or aggressive exposure conditions such as a marine environment and industrial zones in addition to defect states of deterioration [3]. Once this starts to take place, costs of repairs usually increase strict implementation of a lower capacity bearing leading to even failures before time on construction. Hence, enhancing any resistance of concrete regarding these deleterious processes has become a major concern of focus in modern construction [4]. The inclusion of Supplementary Cementitious Materials (SCMs) such as fly ash, GGBS, or silica fume has emerged as a sound technique to ameliorate the microstructure of concrete, lower permeability, and prolong service life, rendering it more durable for corrosive environments [5].

Actions related to using construction materials and above governance processes closely in developing dependence on infrastructural demand globally at a level not letting concern for environmental aspects and dire need for sustainability boast high performance from construction materials be worth the days practice [6]. The production of conventional Port-land cement is highly energy-consuming and contributes to carbon dioxide (CO_2) emissions, accounting for almost 8 percent of global greenhouse gas emissions. The construction sector is obtaining ways to tread the course of rapid urbanization while being dutiful towards the environment; thus, there is a growing urge to practice material that may minimize ecological footprint without necessarily compromising for or improving upon structural performance [7]. Sustainable Construction materials, therefore, tend to minimize the drawdown of resources, the carbon that is embodied through their lifecycle, increase the durability and longevity of structures to limit requirements for maintenance, and overall, lifecycle costs. For instance, high-performance concrete, blended with alternative binders like Supplementary Cementitious Materials (SCMs), solution provides resistance to environmental degradation, enhanced mechanical properties, and use of industrial waste products like fly ash, GGBS, and silica fume [8]. Such materials would divert

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waste from landfills, yet they use fewer energy costs to manufacture than regular cement, in step with construction practices towards global sustainable objectives, such as those espoused in the United Nations' Sustainable Development Goals (SDGs). Thus, in all tenacity, therefore, sustainable and high-performing construction materials would not be an option but rather the order of the day to produce resilient, eco-friendly, and future-ready infrastructures.

Fly Ash is one of the most commonly used supplementary cementitious materials and is primarily obtained as a by-product from the combustion of coal in thermal power plants. Fly ash contains fine powdery earth with mainly spherical glassy particles rich in silica and alumina [9]. Fly ash is classified as Class F (low calcium) and Class C (high calcium) and pozzolanic acts, because it reacts together with calcium hydroxide in the presence of water, forming more calcium silicate hydrate (C-S-H) gel in concrete and refining the pore structure and reducing permeability; further enhancing the long-term strength and durability. With its relatively easy availability and inexpensiveness fly ash is employed greatly in concrete for adding sulphate attack resistance, lowering temperature of hydration, and prolonging life in service of structural components [10].

Ground granulated blast furnace slag or GGBS, or slag cement, is a by-product of the iron and steel industries. Molten slag or waste material from a blast furnace is chilled very rapidly to form a glassy granular material, then ground to fine powder. GGBS has latent hydraulic properties, that is, it is capable of hydrating and hardening from water alone, especially in the alkaline activity of cement [11]. The use of GGBS in concrete improves workability, reduces the risk of alkali-silica reaction (ASR), increases resistance to chloride and sulphate penetration, and significantly lowers the overall heat of hydration. It is light in colour and slow in hydration, thus making a concrete surface more beautiful and durable, especially in massive structures and marine environments [12].

Fly ash

GGBS

Figure 1 Sample images of fly ash and GGBS [58]

The figure 1 shows two types of supplementary cementitious materials: finely powdered Fly Ash on the left and granular Ground Granulated Blast Furnace Slag (GGBS) on the right. Silica fume is a by-product from the silicon and ferrosilicon alloy industries that offer ultrafine, highly reactive amorphous silicon dioxide. Roughly 100 times smaller than cement in particle size, it acts as both pozzolan and micro filler [13]. Denser C-S-H gels are produced due to reaction between rapidly available silica fume and calcium hydroxide. This fact greatly contributes to improving the microstructure of concrete matrix. It fills voids created between cement particles, increasing strength and impermeability, while also reducing porosity. Concrete with silica fume is referred to as very high early strength concrete and is highly resistive to chemical attacks and has very high durability, thus making it a suitable material for applications such as paving of bridge decks, parking structures, and industrial floors [14]. It is very high priced compared to other SCMs, but the performance benefits make it an attraction for high-performance and niche applications. Figure 2 shows granulated Ground Granulated Blast Furnace Slag (GGBS), a commonly used supplementary cementitious material known for enhancing concrete durability and sustainability.

Figure 2 Silica Fume [59]

II. PROPERTIES OF SELECTED SCMS

Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), and Silica Fume (SF) are all entirely different materials which distinguish their properties. Fly Ash mostly consists of silica, alumina, and iron oxides with pozzolanic behaviour, which reacted with calcium hydroxide to form an additional cementitious compound and then get matured gradually to improve the durability and strength [15]. Fly Ash has its classification as Class F (low-calcium, usually from bituminous coal) or Class C (high-calcium, generally from lignite or sub-bituminous coal) and has different performance indicators. GGBS is a by-product from iron making and is called latent hydraulic because it can hydrate in the presence of water and alkaline medium. This will create a lower heat of hydration and improve the long-term strength while improving the performance characteristics for chemical attacks, especially in sulphate and chloride-rich environment [16]. This is an ultrafine powder and rich in amorphous silicon dioxide; silica fume acts as both highly reactive pozzolan and also an effective micro filler. It's extremely fine particle size enables it to effectively fill voids within concrete matrix resulting in very dense microstructure with much lower permeability along with rapid early strength and durability improvements. Together with these SCMs, they greatly enhance the performance, longevity, and sustainability of concrete [17].

A. Fly Ash (FA)

Fly Ash (FA) is derived from fine, powdery fragments of the material created as a by-product of coal burning in thermal power plants. Silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), along with variable proportions of calcium oxide (CaO) depending on the kind of coal burnt, make up most of the chemical composition. These oxides contribute greatly to the quality of fly ash and the reactivity of the ash in cementitious systems, within which it is put into use [18]. When added to concrete, fly ash additionally serves to bring together extra calcium silicate hydrate (C-S-H), responsible for strength and durability at later ages. The presence of glassy spherical particles in fly ash also increases workability and reduces the water required in concrete mixes [19].

Fly ash is identified as pozzolanic, which means it forms additional C-S-H gel when reacting with the calcium hydroxide (CH) derived from cement hydration in the presence of moisture. This reaction augments the microstructure of concrete, wherein pore structure is made finer, permeability is lowered, and the resistance of concrete to chemical attacks-such as exposure to sulphates or penetration to chlorides-is increased [20]. Fly ash is segregated into two types basically: class F fly ash and class C fly ash. Class F fly ash is considered as the low calcium, high siliceous and aluminous materials fly ash that is highly resistant to sulphate attack and most beneficial for extended gain in compressive strength. The high calcium fly ash under class C may have pozzolanic and hydraulic properties and contributes to early strength developments. Both classes have their beneficial characteristics but are required specifically according to performance requirements in a concrete application [21].

B. Ground Granulated Blast Furnace Slag (GGBS)

Ground granulated blast furnace slag (GGBS) is a by-product of the iron and steel manufacturing process. GGBS is produced when molten slag from a blast furnace is quickly cooled with water to form a glassy granular material, which is then finely ground [22]. GGBS is considered a latent hydraulic material that can hydrate and gain strength in water, especially when activated by alkalinity contributed by Portland cement. GGBS differs from pozzolanic materials in that it can independently contribute to the hydration process of calcium silicate hydrate (C-S-H), which is the primary binder responsible for the strength and durability of concrete [23]. Because of its relatively more sluggish rate of reaction compared to ordinary cement, GGBS lends itself to a gradual strength development, an advantage in cases concerning mass concrete structures where the rise in temperature must be controlled during the early age [24].

The greatest asset of GGBS in concrete has been its ability to lower the heat of hydration to withstand bulk pouring and structural forms susceptible to thermal cracking. GGBS tempers temperature rise during early hydration, thereby aiding in structural integrity and minimizing internal stresses [25]. Concrete containing GGBS also shows better strength and durability over time, primarily due to the refinement of pore structure, decreased permeability, and enhanced resistance to aggressiveness from agents like chlorides and sulphates. Thus, the continuous hydration of GGBS provides strength gain well beyond 28 days, often stronger than that of conventional cement in terms of long-term performance [26]. These qualities qualify GGBS as an ingredient in sustainable and durable concrete for infrastructure and maritime applications.

C. Silica Fume (SF)

Silica fume (SF) is an ultrafine, highly reactive by-product of the production of silicon or ferrosilicon alloys. It consists mostly of amorphous silicon dioxide (SiO_2), with particle sizes about 100 times smaller than cement, thus possessing a very high specific area [27]. In addition, the ultrafine particle size enables silica fume to fill microscopic voids between cement grains, thereby improving particle packing and lowering the overall porosity of the concrete matrix. In addition to this physical property, silica fume possesses an extraordinarily high pozzolanic activity as it rapidly reacts with calcium hydroxide formed during cement hydration, thereby producing additional calcium silicate hydrate (C-S-H) gel, the main strength-providing component of concrete [28].

The combined effects of its filler action and high chemical reactivity result in a much denser and refined microstructure in silica- fume-modified concrete. The silica fume also leads to reducing permeability, aiding the resistance against any attack concerning chemicals, and enhancing the property, especially compressive strength, the helpful microfiber matrix [29]. This also results in microstructural densification limiting the ingress of damaging agents such as chlorides, carbon dioxide, and sulphates, tremendously enhancing the structure's durability and service life. However, due to high surface area and affinity for water, silica fume is recommended in small quantities (5-10% by weight of cement) and is usually used in conjunction with superplasticizers to ensure workability. In general, silica fume is one of the most significant supplementary cementitious materials for producing high-performance and durable concrete, especially in harsh environments [30].

III. PARAMETERS INFLUENCING DURABILITY PERFORMANCE

Concrete with supplementary cement materials (SCM), such as fly ash, GGBS, and silica fume, is affected in its durability performance by many major parameters: the replacement level of SCM, water-to-binder ratio, curing method, particle size, and mix proportions. The lower the water-to-binder ratio and with good curing, the higher the hydration and lower are permeability, whereas in an optimized scenario, the SCM dosage will enhance pore refinement and resistance to chemical attacks. Another aspect of SCMs that affect their contribution to improving concrete microstructure and long-term durability is their fineness and reactivity.

A. SCM Replacement Level

The Durability of Concrete is greatly affected by the percentage of Portland cement that is replaced with supplementary cementitious materials as it governs the concurring performance and sustainability. Replacement level of SCMs such as Fly Ash, GGBS, and Silica Fume-regard; Portland cement that helps create long-term durability in concrete by refining pore structure and reducing permeability, thus improving resistance to all kinds of chemical attack. The right replacement percentages pay a pivotal role in durability problems such as alkali-silica reactivity (ASR), chloride-ion ingress, sulphate attack, and moisture transport. However, it is essential to note that while proper dosages greatly enhance concrete service life, excessive replacement brings particular disadvantages related to early-age strength development, setting time, and workability, mainly when there is no adequate adjustment of mix design or use of chemical admixtures [31]. The best dosage is specific to the type of SCM used-fly ash is typically 15-30% by mass, giving significantly improved workability and long-term strength gains; GGBS is usually used at 30-50% as it has hydraulic properties and is resistant to chemical attacks; silica fume is most effective at 5-10% because of ultrafine particle size and very high pozzolanic activity, improving density and impermeability. Thus, determination and application of proper replacement levels may lead to the right balance between mechanical performance and durability maintenance while letting the concrete perform well under different environmental exposure conditions with regard to sustainability issues [32].

B. Water-to-Binder Ratio (w/b)

Water-to-binder ratio (W/B) is the primary factor influencing durability performance of concrete, particularly with mix containing supplementary cementitious materials (SCMs). This ratio governs the porosity of hardened concrete, which in turn affects permeability, strength, and environmental deterioration resistance. Lower W/B ratios offer, in general, a dense compact microstructure leading to significantly reduced ingress of harmful substances such as chlorides, sulphates, and carbon dioxide being the causatives for common durability problems like corrosion, carbonation, and sulphate attack [33]. On the other hand, higher W/B ratios produce more capillary porosity in concrete, which slowly leads to moisture penetration, cracking, and chemical degradation. Due consideration should be given to choosing the minimum permissible water-to-cement ratio while still allowing proper hydration and workability, especially for mixes containing SCMs. Because Fly Ash, GGBS, and Silica Fume influence the water demand and setting characteristics of the mix, the use of superplasticizers and other water-reducing admixtures should be modified to maintain the desired performance and workability of concrete or mortar without compromising durability. Further, the attainment of the most appropriate W/B ratio promotes binder hydration and strength development and helps determine the service life and resistance of concrete constructions to aggressive environments [34].

C. Curing Conditions and Duration

It is proper curing that lets concrete fully reveal its durability potentials, especially when it is made with supplementary cementitious materials (SCMs) like fly ash, GGBS, and silica fume. These materials usually take a longer time than ordinary Portland cement while pozzolanic or hydraulic processes take place, during which time they need to remain moist and kept in favourable temperatures for a reaction with development of the strength and durability. Proper curing keeps going hydration, which is necessary in developing a tight microstructure and reduced capillary porosity [35]. All beneficial reactions of SCMs may be incomplete if proper curing has not been done, especially at early ages, leading to a weak and porous matrix that becomes increasingly vulnerable to chemical ingress, such as chlorides, sulphates, and carbon dioxide. Such deteriorations culminate to a marked loss in durability indicators like permeability resistance, sulphate attack resistance, and protection against reinforcement corrosion. Thus, prolonged curing periods and proper curing methods-water curing; wet coverings, or curing compounds-must be used for SCM-based concrete in order to secure both the best performance and the long-term structural integrity, especially under aggressive environmental exposures [36].

D. Fineness and Particle Size

The particle size and fineness of supplementary cementitious materials (SCMs) play a crucial role in determining their effectiveness in enhancing concrete durability. Finer particles have a larger specific surface area, which directly influences their reactivity and the speed at which they participate in pozzolanic or hydraulic reactions. Ultrafine SCMs such as silica fume are especially effective in improving concrete's microstructure due to their dual function—acting both as a highly reactive pozzolan and as a micro filler. Their extremely small particle size allows them to fill microscopic voids within the cement matrix, significantly reducing porosity and permeability [37]. This refinement in the pore structure enhances resistance to the ingress of harmful agents like chlorides, sulphates, and carbon dioxide, which are major contributors to durability-related deterioration. In contrast, SCMs with coarser particle sizes, such as some low-grade fly ash or poorly ground slag, may exhibit delayed reactivity, leading to slower strength development and a less dense microstructure. If not properly optimized in the mix design—through adjustments in dosage, water content, or blending with finer materials—these course SCMs can negatively impact durability. Therefore, understanding and controlling the particle size distribution of SCMs is essential to achieving the desired improvements in long-term performance and durability of concrete [38].

IV. DURABILITY INDICATORS WITH EVALUATION TECHNIQUES

To assess how materials or systems behave with the passage of time entails recognizing indicators of specific types of wear or degradation, known as durability indicators, and employing suitable evaluation techniques to quantify them. These indicators might be indicative of properties such as resistance to stress, corrosion, or fatigue, as well as environmental influences. Methods of evaluation include laboratory tests, in-service monitoring, and predictive modelling, all of which relate quantifiable indices to insight into the material or structure over time [39]. The link between the indicators and techniques is paramount to safety, design enhancement, and extension of service life, for products or structures.

A. Resistance to Chloride Ion Penetration (RCPT, Migration Tests)

Concrete uses reinforcing bars. Apart from strength, these bars should give durability to the constructed structure. Some of the common troubles faced towards this objective are the corrosion of steel members embedded in concrete, mainly due to ingress of chloride ions. This leads to a serious point of concern with regard to durability under conditions typically induced by marine environments or de-icing salts. The two methods that are generally adopted to assess the resistance of concrete against chloride ingress are Rapid Chloride Permeability Test (RCPT) and chloride migration tests [40]. The RCPT consists of measuring the whole electrical charges passed through a concrete specimen within a specific time, traditionally this duration is six hours and consequently provides an indirect measure of permeability of material toward chloride ions, since higher charge indicates more permeability and consequently higher risk of corrosion. The chloride migration methods include NordTest through which electrical field is applied to accelerate chloride migratory flow in a saturated concrete sample so that accurate chloride diffusion coefficient for long run performance could be calculated. Both these tests prove very useful in understanding how well and for what duration concrete would last under conditions of exposure. Lower permeability or diffusion values serve to indicate a denser microstructure and hence more resistance to chloride-induced corrosion, ultimately leading to a long-lasting structure requiring reduced maintenance in aggressive environments [41].

B. Sulphate Attack Resistance

Thus, spewing sulphate ions from the ground into the soil or groundwater brings about chemical deterioration within concrete structures. These ions subsequently interact with important hydrated compounds found in cement paste, causing expansion, internal cracking, and gradual reduction in the strength of concrete. Decrease in strength levels within the concrete may be unusual; however, such degradation is especially critical for areas where the structures are permanently under sulphate-rich media, such as foundations, sewage, and marine infrastructure [42]. Inclusion, however, is supplementary with other cementitious materials, especially fly and ground granulated blast furnace slag (GGBS), as an alternative concrete construction material and can therefore considerably increase sulphate attack resistance in concrete. Notably, this is done through reduced calcium hydroxide content and refinement of pore structures which limits the ingress of ions. In laboratory conditions, concrete specimens are usually subjected to sulphate immersion, and the performance assessment done over time uses mass change, dimensional expansion, and reduction in compressive strength as parameters. For this kind of test, an understanding of the durability performance of concrete against sulphate exposure can lead an engineer into designing structures that will yield a longer service life and less possibility of premature failure by aggressive conditions [43].

C. Carbonation Resistance

Carbonation, on the other hand, is a chemical process whereby carbon dioxide from the atmosphere reacts with calcium hydroxide in concrete, which then lowers the pH enough to depassivate the protective layer around steel reinforcement and trigger corrosion. This phenomenon is a serious durability concern, especially in those structures where the concrete cover is less than 30 millimetres or in which the concrete mix design is of poor quality [44]. Carbonation resistance is, therefore, determined usually in the laboratories by exposing concrete specimens to accelerated CO_2 environments and measuring the depth of carbonation with an indicator such as phenolphthalein, which indicates the change in pH by a colour change. On the contrary, supplementary cementitious materials (SCMs) like fly ash and ground granulated blast furnace slag (GGBS) may increase carbonation depth marginally compared to normal concrete owing to a decreased availability of calcium hydroxide from the hydration process. This potential drawback can be effectively countered through an optimized mix design, proper curing, and good concrete cover, thus allowing long-term durability and protection of the embedded steel reinforcement [45].

D. Water Permeability and Sorptivity

Water permeability and sorptivity tests are conducted to determine how easily water enters or is absorbed by concrete, which will, in turn, influence its durability in the long term. Increased permeability/sorptivity hastens the rate of transportation of harmful chemicals and freeze-thaw damage, increasing the risk of corrosion of reinforcements under very aggressive conditions [46]. The use of supplementary cementitious materials (SCMs) particularly silica fume is very important in improving durability mainly by modifying the pore structure and greatly reducing the volumes of capillary pore spaces, thus lowering both water absorption and permeability. In laboratory measurements, these tests consist of the determination of either the volume of water that passes through a concrete specimen or the rate with which it enters the surface over a given time period [47]. Lower test values mean a denser, less porous concrete matrix, which translates to improved resistance to moisture-related deterioration and thus the overall resilience and longevity of the structure.

E. Freeze-Thaw Durability

Moisture within concrete can freeze, expand, and cause internal pressure to build, leading to the development of cracks and scaling on the surface, if subjected to cyclic freezing and thawing in certain regions. An assessment of freeze-thaw durability is carried out by placing concrete specimens through multiple temperature cycles in a controlled freeze-thaw chamber, where posttest records keep track of mass loss, surface damage, and changes in dynamic modulus as performance criteria [48]. SCMs are beneficial in augmenting resistance by reducing permeability, thus reducing the availability of more water to freeze in the pores. Still, proper distribution of entrained air is an important consideration, for it creates microscopic voids to accommodate the expansion of freezing water and relieve internal stresses. An appropriately proportioned concrete mix that uses SCMs plus correct air entrainment affords the best defence against freeze-thaw damage for improving structural durability and longevity in cold or variable climatic views [49].

F. Mitigation of Alkali-Silica Reaction (ASR)

The alkali-silica reaction (ASR) is a destructive process whereby alkalis in the cement react with reactive forms of silica present in aggregates and give rise to the formation of an expansive gel that absorbs moisture, swells, and causes cracking in concrete. The ASR process is detrimental to the structural and durability performance of affected members over time [50]. The incorporation of supplementary cementitious materials (SCMs), such as fly ash and ground granulated blast-furnace slag (GGBS), counters the ASR process by reducing the concentration of reactive alkalis in the concrete. At the same time, it reduces the amount of Ca (OH)2, which inhibits gel formation and expansion. For ASR testing, the mortar bars/concrete prisms are placed for accelerated moisture-induced ASR potentials with high temperatures and high humidity. The dimensional changes are monitored over a period of time. A clear manifestation of ASR control light is in significantly reduced expansions, particularly below the prescribed threshold limits, which underpins the significance of the selection of a material and mix design in stopping this particular form of deterioration [51].

A large array of waste and natural materials is acknowledged as Supplementary Cementitious Materials (SCMs) to replace clinker to reduce CO_2 emissions, but literature lacks clear criteria on which SCM should be chosen for a project. A review of over twenty SCMs in India assesses availability, physical, and chemical characteristics affecting properties of concrete, and environmental impacts, showing a national surplus of 380 Mtpa against a demand of 105 Mtpa albeit with regional imbalances. The SCMs that are similar in size and shape to cement enhance workability while the fine, Ca-rich SCMs enhance strength and durability, with recommendations provided for sustainable multi-blended cement utilization [52]. Since sustainability has become an important policy issue, blended cements, with the presence of SCMs - often by-products of the industry- reduce emissions and preserve resources, although the rising demand and limited supply of high-quality SCMs necessitate alternative SCMs (ASCMs). Local and variable, the ASCMs would demand rapid evaluation techniques for qualification of SCM, and also for material inventories-all outlined in [53]. In 3D concrete printing (3DCP), the use of SCMs becomes crucial in reducing the high Portland cement content dependency and in aiding printability and emission reduction. This study assesses SCMs such as fly ash, silica fume, slag, and metakaolin in alkaline and non-alkaline 3DPC systems, evaluating their effects on rheology, mechanical behaviours, curing, and shrinkage, and identifies challenges and research areas for future investigation [54]. Metakaolin, the calcined product of kaolinite, affects concrete microstructure and durability in particular for high-performance and self-compacting concrete [55]. Fiber Reinforced Polymer (FRP) bars and SCM-based concrete combinations provide durability as well as improve on low environmental impact, with research showing that carbonation in SCM concrete could slow FRP degradation, particularly in the case of BFRP applications [56]. Calcined marl is another feat and an encouraging SCM, which has been studied in-depth with respect to its chemical and physical properties, activation methods, and compatibility issues on the road to producing highly reactive and eco-friendly cement blends [57].

Table 1 Comparative Analysis of SCM-Based Research with Emphasis on Durability, Sustainability, and Emerging Applications

Reference	Focus Area	Key Materials Discussed	Sustainability Aspect	Limitations
[52]	General SCMs in India	Fly Ash, GGBS, Silica Fume, Others (20+ SCMs)	CO_2 reduction, Utilization of excess SCMs, Regional balance	Lack of selection criteria, regional imbalances
[53]	Alternative SCMs (ASCMs)	Locally sourced ASCMs with variable composition	Carbon emission reduction, Waste minimization, Local availability	Scarcity of high-quality SCMs, Evaluation methods needed
[54]	SCMs in 3D Printed Concrete (3DPC)	Fly Ash, Silica Fume, GGBS, Metakaolin	Reduce Portland Cement use, Operational efficiency	High PC use in 3DPC, Need for printable mix design
[55]	Metakaolin	Metakaolin	Improves packing, reduces bleeding, eco-friendly mix	High replacement ratio issues, Compatibility
[56]	SCMs with FRP Bars	Various SCMs + Basalt FRP (BFRP) Bars	Reduced emissions, Extended FRP durability, Sustainable structures	Interaction with FRP in

				alkaline/corrosive environments

V. CONCLUSION

A thorough parametric appraisal of supplementary cementitious materials, particularly fly ash, ground granulated-blast-furnace slag, and silica fume, has revealed that potential remains for these materials in influencing concrete long-term durability and sustainability. Indeed, these SCMs improve concrete performance against serious deterioration processes: chloride ingress; sulphate attack; alkali-silica reaction (ASR); carbonation; freeze-thaw; acid attack; and remediation of its microstructure by reducing pore space into fine, high-permeability pore sizes. The addition of SCMs also further reduces the water-to-binder ratio, permeability, and resistance to chemical attack, thus enhancing the durability of concrete against aggressive environments. In addition, SCMs help mitigate the environmental impact caused by production of Portland cement, which significantly contributes to worldwide CO_2 emissions. Different kinds of SCMs work for improvement of mechanical and durability performance by virtue of their chemical composition, particle size, and pozzolanic or hydraulic activity. Whereas fly ash improves long-term strength and sulphate resistance, GGBS contributes to resistance to chloride penetration and thermal cracking, and silica fume greatly enhances early strength and impermeability. Replacement level, curing method, and fineness are also important parameters that should be maximized for these gains. In conclusion, the findings of this work highlight the importance of SCMs as key ingredients in high-performance, environmentally friendly concrete mixtures that satisfy the demands of modern infrastructure while achieving global sustainability targets.

Conflict of Interest: The corresponding author, on behalf of second author, confirms that there are no conflicts of interest to disclose.

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