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Supplementary Cementitious Materials for Sustainable Cement and Concrete: Sources, Reactivity, Hydration Mechanisms, Performance, Durability and Emerging Pathways- A Critical Review

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Abstract
Supplementary cementitious materials (SCMs) are central to the transition toward lower-clinker and lower-carbon cementitious binders. They can reduce clinker demand while modifying hydration, pore structure, strength development and resistance to aggressive environments. Conventional SCMs such as fly ash, ground granulated blast-furnace slag and silica fume have an extensive performance record, but their future availability is increasingly uncertain and varies geographically. Consequently, natural pozzolans, calcined clays, zeolites, agricultural ashes, waste glass, processed industrial residues and other emerging materials are receiving increasing attention. This review synthesizes the supplied literature on SCM classification, physicochemical characteristics, reaction mechanisms, characterization, fresh and hardened properties, durability and sustainability. Particular emphasis is placed on the interaction between chemical composition, amorphous content, fineness, replacement level, curing conditions and SCM reactivity. The review also discusses the importance of distinguishing filler, pozzolanic and latent-hydraulic effects and highlights the limitations of conventional qualification tests when applied to nontraditional SCMs. Calcined-clay–limestone systems are considered as an important example of multi-component clinker reduction, while agricultural residues, natural zeolites, pumice, perlite, waste glass, steel slags and recycled ashes illustrate the diversity of emerging sources. The review concludes that future SCM deployment should be based on performance-oriented qualification, robust characterization, source-specific processing and optimized combinations of complementary materials rather than on a single universal replacement level. A research framework is proposed linking source identification, processing, reactivity testing, mixture optimization, durability assessment and life-cycle evaluation.

Keywords: *Supplementary Cementitious Materials; SCMs; fly ash; slag; silica fume; calcined clay; natural pozzolan; zeolite; agricultural ash; LC^3; durability; low-carbon concrete*

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I. Introduction

Concrete is the dominant construction material for infrastructure, and its global scale makes the environmental performance of its binder system particularly important. Portland-clinker manufacture is energy intensive and involves both fuel-related emissions and process emissions from limestone decarbonation. Consequently, clinker substitution has become one of the principal routes for reducing the environmental intensity of cement and concrete [1-7]. Life-cycle studies further show that the magnitude of the benefit depends on the origin, processing, transport and allocation procedure assigned to an SCM; therefore, the environmental advantage of a particular material should not be assumed without considering its complete supply chain [2,3,5,8].

SCMs are broadly defined as finely divided siliceous, aluminosiliceous or calcium-aluminosiliceous materials that contribute to cementitious performance through pozzolanic and/or hydraulic reactions and, in some cases, primarily through physical filler effects [16,78,79]. Their use can reduce clinker content, consume industrial or agricultural residues and improve selected mechanical and durability properties. Earlier work demonstrated that silica fume can enhance early strength and reduce permeability, whereas fly ash and slag generally develop strength more slowly and can require extended curing [75]. Modern research has expanded the field from conventional industrial by-products toward calcined clays, natural pozzolans, zeolites, pumice, perlite, processed wastes and other mineral resources [11,16-21,24-28].

A major challenge is that SCMs are not a single material class. Their reaction depends on mineralogy, amorphous fraction, particle size distribution, specific surface area, glass chemistry, calcium and alumina contents, replacement level, water availability, temperature and pore-solution chemistry [11,16,53,57-61,77]. Even materials nominally belonging to the same category can therefore exhibit markedly different reactivities. This variability is particularly important when conventional qualification procedures are transferred to alternative SCMs [11,12,28].

The objective of this review is to provide an integrated assessment of SCMs from source to performance. The review first classifies SCMs and explains their principal reaction mechanisms. It then examines conventional and emerging SCMs, characterization and reactivity testing, fresh and hardened properties, durability, sustainability, and multi-component binder design. Finally, research gaps and a practical qualification framework are identified.

II. Classification and Fundamental Role of SCMs

SCMs can be grouped according to their origin and dominant reaction mechanism. Industrial by-products include coal fly ash, blast-furnace slag and silica fume; natural materials include volcanic ash, pumice, zeolites and other natural pozzolans; thermally activated minerals include calcined kaolinitic and other clays; and processed wastes include agricultural ashes, ground glass, dredged sediments, municipal-incineration residues and selected metallurgical wastes [13,16,31,63-67].

SCMs can act through three overlapping mechanisms. First, a filler effect improves particle packing and may accelerate clinker hydration by providing nucleation surfaces. Second, pozzolanic reaction consumes calcium hydroxide released by clinker hydration and produces additional calcium-silicate-hydrate (C–S–H), calcium-aluminate-silicate-hydrate (C–A–S–H) and/or aluminate-bearing phases. Third, latent-hydraulic materials react with water in an alkaline environment and form cementitious hydrates, with slag being the principal conventional example [45,53,54,79]. These mechanisms operate simultaneously rather than independently. The overall mechanistic pathway, from SCM dissolution and portlandite interaction to secondary hydrate formation and microstructural refinement, is illustrated in Figure 1.

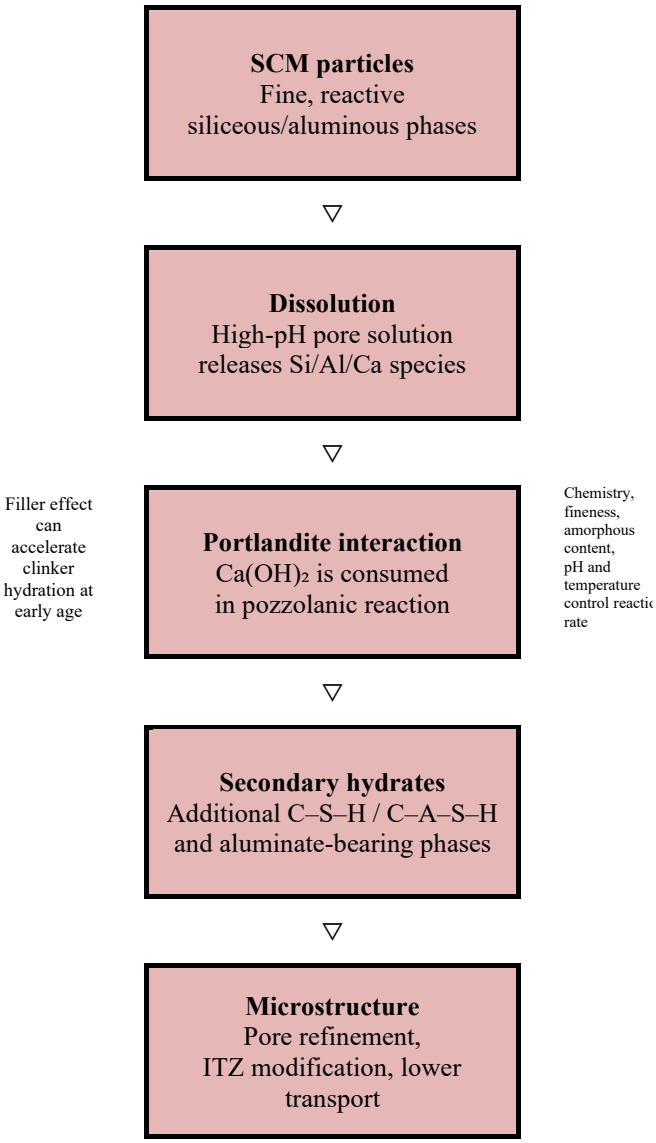


Figure 1. Mechanistic pathway of SCM action in Portland-cement systems.

The chemistry of the SCM strongly influences the resulting hydrate assemblage. Silica-rich materials tend to reduce portlandite and lower the Ca/Si ratio of C–S–H, whereas alumina-rich materials increase Al incorporation into C–S–H and can promote AFm-type and other aluminate-bearing hydrates [79]. Limestone can also participate chemically in systems containing reactive alumina, promoting carboaluminate phases; this interaction is particularly important in limestone–calcined-clay systems [42-49]. The overall performance is therefore governed by the combined chemistry of clinker, SCMs and fillers rather than by the SCM considered in isolation.

The present review is based primarily on the supplied peer-reviewed papers and review articles, with emphasis on studies addressing conventional SCMs, alternative sources, reactivity, hydration and durability. The source set includes experimental investigations of fly ash, silica fume, slag and zeolite; broad reviews of SCM mineralogy and reaction; studies of natural pozzolans, calcined clays and LC^3; and investigations of agricultural and industrial waste-derived materials. The synthesis therefore combines evidence from material-scale characterization, paste/mortar studies and concrete performance studies. Where the literature reports apparently different outcomes, the differences are interpreted in relation to curing, replacement level, fineness, source chemistry and test conditions rather than treated as universal contradictions.

The review also distinguishes three levels of evidence. At the first level are intrinsic material properties such as chemical composition, mineralogy, amorphous fraction and particle size. At the second level are binder-scale phenomena including dissolution, heat evolution, portlandite consumption, hydrate formation and pore refinement. At the third level are engineering outcomes such as workability, strength, permeability and durability. A useful SCM must perform adequately across these levels. A material can have high measured pozzolanicity but still be unsuitable at a practical dosage because of excessive water demand, delayed setting, expansion, contamination or poor long-term durability. Conversely, a relatively slowly reacting material can become valuable when used in a ternary binder where its particle packing and later-age reaction complement a faster SCM.

This multi-scale perspective is consistent with the recent shift from simply identifying "new SCMs" toward developing methods for comprehensive qualification [11,16,28,77]. It is also consistent with evidence that physical effects and chemical reactions cannot always be separated experimentally [52-54,57]. Therefore, replacement percentage is used in this review only as one design variable; it is not treated as a universal indicator of environmental or technical performance.

2 .1 Reaction kinetics and hydrate evolution

For pozzolanic SCMs, the reaction can be simplified conceptually as dissolution of reactive silica and/or alumina under high-pH conditions followed by interaction with calcium-bearing species and other components of the cementitious pore solution. A simplified silica reaction is often represented as consumption of $Ca(OH)_2$ and formation of additional C-S-H, although actual blended-cement systems contain Al, alkalis, sulfate and carbonate and therefore form more complex assemblages [45-49,79]. The reaction rate is controlled by dissolution kinetics, available surface area, solution chemistry and diffusion through reaction products.

The filler effect can operate before substantial SCMs reaction occurs. Fine particles provide nucleation sites for clinker hydrates and alter local packing. Consequently, an SCM can accelerate the apparent hydration of clinker even while the SCM itself reacts slowly [52-54,57]. This distinction is important when interpreting calorimetry or early-age strength. A higher early heat release does not necessarily mean that the SCMs has reacted extensively; part of the response may result from enhanced clinker hydration.

As reaction proceeds, the reduction in portlandite and the formation of secondary hydrates can reduce capillary pore connectivity. Silica-rich SCMs generally lower the Ca/Si ratio of C-S-H, while alumina-rich SCMs promote greater Al incorporation and additional aluminate-bearing hydrates [45-49,79]. Carbonate-bearing binders introduce further interactions because reactive alumina can form carboaluminate phases. The resulting phase assemblage affects sulfate resistance, chloride binding, pore structure and carbonation behavior.

Temperature is another critical kinetic variable. Higher temperature generally accelerates dissolution and hydrate formation, but it can also alter the structure and distribution of hydrates and may reduce the relative benefit of slowly reacting SCMs if curing is not representative of field conditions. Water availability and relative humidity are equally important. Because some SCMs have substantial internal porosity or water-retention capacity, their influence can extend beyond chemical reaction to internal curing and shrinkage mitigation [23,26,27].

A practical implication is that SCM optimization should target a desired reaction trajectory rather than simply a high reactivity index. A very reactive SCM may consume water rapidly and increase autogenous or drying-shrinkage sensitivity if mixture rheology is not controlled, while a slowly reacting SCM may be advantageous for long-term densification and heat management. Multi-component systems can exploit these differences by pairing materials with complementary kinetics [42-49,53,54].

III. Conventional SCMs

3.1 Fly Ash

Fly ash has historically been one of the most widely used SCMs. Its performance depends strongly on particle morphology, glass content,

calcium content, carbon content and fineness. Reactive glassy phases dissolve in the alkaline pore solution and participate in secondary hydrate formation. The reaction is generally slower than clinker hydration, explaining why fly-ash concrete may exhibit lower early-age strength but substantial later-age strength development when adequate curing is provided [9-12,53,57,72-75]. The supplied experimental study by Toutanji et al. showed that short-term curing can disadvantage fly-ash-containing mixtures and emphasized the importance of extended curing for strength and durability development [75].

Fly ash also illustrates the importance of material beneficiation. Wet storage, high carbon content, variable fineness and chemical heterogeneity can limit direct utilization. Reclamation and processing strategies can expand the usable resource base [9,17,72,73]. However, the decline of coal-fired power generation in some regions means that traditional fly ash supply cannot be assumed to increase in proportion to cement demand [5,7,9,10]. This supply issue is a major reason for developing alternative SCMs.

3.2 Ground Granulated Blast-Furnace Slag

GGBFS is a latent-hydraulic material produced by granulating and grinding suitable blast-furnace slag. Its reaction is influenced by glass composition, fineness, temperature and the alkalinity of the cementitious environment. Slag generally contributes to lower permeability and improved later-age performance, although high replacement levels may reduce early-age strength unless curing and mixture design are optimized [53,54,79]. The future availability of slag is also tied to the production of iron through blast-furnace routes; therefore, its supply may decline as steelmaking technologies change [7,16].

3.3 Silica Fume

Silica fume is an extremely fine, silica-rich material with high pozzolanic activity. Its small particles provide a strong filler effect and its reaction with portlandite generates additional C–S–H. The result can be a refined pore structure, lower permeability and increased strength, especially when dispersion is achieved with appropriate water-reducing admixtures [75,79]. Its very high surface area, however, can increase water demand and reduce workability. Silica fume is therefore commonly used at relatively modest replacement levels or in combination with other SCMs.

IV. Natural Pozzolans, Zeolites and Volcanic Materials

Natural pozzolans include volcanic ash, tuff, pumice and zeolitic materials. Their performance is controlled by mineralogy, volcanic history, glass content, particle size and the presence of reactive aluminosilicate phases [13-19]. Pumice performance is strongly affected by particle size; finer material generally increases reactivity but may increase water demand [19]. Perlite can also be activated by additional milling, illustrating the role of mechanical processing in unlocking natural resources [20].

Natural zeolites are unusual because their pozzolanic contribution can arise from crystalline framework aluminosilicates rather than predominantly amorphous glass. The supplied zeolite study reported good pozzolanic reactivity and improvements in strength and durability-related properties, including resistance to alkali–silica expansion under the investigated conditions [79]. Subsequent studies show that zeolite reactivity and workability can be modified by calcination, acid treatment or milling [23-26]. Zeolites may also contribute to internal curing because of their porous structure and water-retention capacity [26].

The principal advantage of natural SCMs is that some require substantially less processing than clinker. Their principal challenge is source variability. Two deposits classified as the same mineralogical type may behave differently because of differences in glass fraction, reactive phases and fineness. This makes source-specific qualification essential [13,16,18,28,29].

V. Calcined Clays and Limestone–Calcined-Clay Systems

Calcined clays are among the most promising alternatives to conventional SCMs because suitable clay deposits are geographically widespread. Heating transforms clay minerals into disordered, reactive aluminosilicate phases. Kaolinite-rich clays generally exhibit high reactivity after appropriate calcination, while illitic and mixed clays require careful optimization of mineralogy and thermal treatment [30-36]. Low-grade clays can also become viable SCMs when calcination and grinding are controlled [34-37].

Limestone–calcined-clay cement (LC^3) is a particularly important multi-component system. Calcined clay supplies reactive silica and alumina, while limestone supplies carbonate and filler effects. The reactive alumina can interact with carbonate-bearing phases to form carboaluminate hydrates, while the combined filler and pozzolanic effects promote efficient binder packing and hydrate development [42-49]. Experimental work has demonstrated competitive mechanical and durability

performance at substantially reduced clinker contents [43,44]. The performance of LC^3 is nevertheless sensitive to calcined-clay quality, calcined kaolinite content, limestone characteristics, sulfate balance and clinker composition [44-49].

A key lesson from calcined-clay research is that "SCM content" alone is an inadequate descriptor. Reactivity depends on the mineralogical transformation achieved during calcination, residual crystalline phases, surface area and the interaction of the calcined clay with clinker and limestone. Industrial calcination therefore needs process control rather than simply a target temperature [34-37].

VI. Agricultural and Other Waste-Derived SCMs

Agricultural residues represent a large and geographically distributed source of silica- and alumina-bearing ashes. Rice husk ash, sugarcane bagasse ash, palm-oil fuel ash, wood ash, bamboo leaf ash and corn-cob ash have been investigated as cementitious materials [63,68-71]. Their potential is attractive because the ash is generated from biomass that would otherwise require disposal or further treatment. The agricultural-waste review supplied with this study emphasizes that many such ashes can contain high silica concentrations, while also noting that their suitability is strongly influenced by burning conditions and particle morphology [63].

Rice husk ash can be highly reactive when combustion is controlled to preserve amorphous silica. Excessively high temperatures may crystallize silica and reduce pozzolanic activity, whereas incomplete combustion can leave high carbon content. Its porous particles can also increase water demand [63]. Sugarcane bagasse ash similarly benefits from selective grinding, classification and controlled processing [68-70]. These examples show that processing is not an auxiliary step; it is part of the SCM design.

Ground waste glass provides another pathway. Finely ground glass can behave as a pozzolan because of its amorphous silica-rich structure, although alkali content and particle size must be considered carefully [67]. Other emerging resources include fluidized-bed-combustion ashes, municipal solid-waste incineration ashes, oil-shale residues and processed dredging or excavated clays [37-40,64-67]. Their use requires stricter source characterization because potentially undesirable constituents may influence durability, leaching, setting or volume stability. The major SCM categories, representative materials, dominant contributions, typical advantages, and principal limitations are summarized in Table 1.

SCM CATEGORY	REPRESENTATIVE MATERIALS	DOMINANT CONTRIBUTION	TYPICAL ADVANTAGES	PRINCIPAL LIMITATIONS
INDUSTRIAL BY-PRODUCTS	Fly ash, GGBFS, silica fume	Pozzolanic/hydraulic + filler	Availability, established performance, reduced clinker	Supply variability and regional depletion
NATURAL POZZOLANS	Volcanic ash, pumice, zeolite	Pozzolanic + filler	Low processing demand for some sources	Mineralogical variability, water demand
CALCINED MINERALS	Metakaolin, calcined low-grade clays	Highly pozzolanic	High reactivity, strong later-age performance	Calcination energy, processing control
AGRICULTURAL ASHES	Rice husk ash, bagasse ash, palm-oil fuel ash, wood/bamboo ash	Pozzolanic + filler	Waste valorization, local availability	High loss on ignition, porous particles, variability
PROCESSED WASTES	Ground glass, dredged sediments, MSWI ash, oil-shale residues	Variable	Circular-economy potential	Contaminants, alkalis, qualification requirements
METALLURGICAL RESIDUES	Steel slags, ferronickel slags	Hydraulic/pozzolanic/filler	Large resource base in some regions	Expansion, free lime/MgO, variable chemistry

Table 1. General classification of SCMs and their principal characteristics. [13–19,21,29–31,38–42,62–74]

VII. Reactivity and Characterization of SCMs

The central scientific problem in SCM utilization is determining whether a candidate material will react beneficially in a cementitious system and at what rate. Traditional strength activity tests provide practical information but can confound reactivity with physical effects. Rapid screening methods, chemical dissolution tests, calorimetry, thermogravimetric analysis and phase characterization can provide complementary information [11,16,28,77].

Suraneni et al. tested a broad range of SCMs using isothermal calorimetry and calcium-hydroxide consumption and demonstrated that SCMs classified under the same broad category can have substantially different reactivities because of differences in amorphous content, chemical composition and fineness [76]. This finding supports a multi-parameter qualification strategy.

Important characterization techniques include X-ray fluorescence for bulk oxide chemistry; X-ray diffraction for crystalline mineralogy and quantitative assessment of amorphous content; laser diffraction for particle-size distribution; thermogravimetric analysis for bound water and portlandite consumption; scanning electron microscopy for morphology; and isothermal calorimetry for hydration kinetics [11,16,29,57-62,77-79]. No single test adequately predicts concrete performance. A summary of the principal characterization properties, commonly used methods, and their relevance to SCM assessment is presented in Table 2.

Property	Typical method	Why it matters
Chemical composition	XRF	Indicates Si, Al, Ca, Mg, Fe, alkalis and sulfate-related chemistry
Mineralogy/amorphous fraction	XRD/Rietveld	Identifies reactive and inert phases
Particle size	Laser diffraction	Controls packing, dissolution and water demand
Surface area	Blaine	Related to reactivity and rheology
Thermal behavior	TGA/DTG	Tracks portlandite consumption, bound water and carbonaceous matter
Hydration kinetics	Isothermal calorimetry	Identifies acceleration, retardation and reaction intensity
Morphology	SEM/EDS	Reveals particle texture and elemental distribution
Pozzolanicity	Chapelle/Frattini/strength activity or modern calorimetric tests	Provides comparative reactivity information
Performance	Strength, permeability, chloride, sulfate, ASR, carbonation	Establishes application-specific suitability

Table 2. Recommended characterization framework for candidate SCMs. [11,12,28-30,57-62,77-79].

VIII. Influence on Fresh and Hardened Properties

SCMs influence workability through particle size, morphology, surface area, porosity and water affinity. Spherical fly-ash particles may improve flow in some systems, whereas angular, porous agricultural ashes and highly reactive fine materials can increase water demand. Zeolite and natural pozzolan additions can reduce slump because of their internal porosity and high surface area [19,21,22,23,79]. The appropriate dosage of chemical admixture can compensate for some of these effects, but excessive dispersant can also alter stability or segregation behavior.

Early-age strength is frequently reduced when a slowly reacting SCM replaces clinker. The magnitude depends on replacement level, curing temperature, fineness and reactivity. In contrast, later-age strength can benefit from secondary hydrate formation and pore refinement [75,79]. High-volume fly ash and slag systems therefore require curing regimes that permit the slower reactions to proceed [75]. Calcined clays and silica fume can develop more rapidly, but their high surface area can increase water demand.

Mechanical performance is not controlled solely by total hydrate volume. The interfacial transition zone, capillary porosity and connectivity of the pore network are important. Fine reactive SCMs can improve packing and reduce connected porosity, while secondary hydration further densifies the paste [45,53,54]. Consequently,

optimized SCM systems may achieve similar or greater later-age strength than a Portland-cement reference despite lower clinker contents.

IX. Durability

Durability benefits are among the most important reasons for SCM use. Refinement of capillary pores reduces permeability and slows transport of chloride ions, water and other aggressive species. Additional hydrates can also modify chemical binding, including chloride binding in alumina-containing systems [42-49,53,79]. Natural pozzolans and zeolites have been reported to reduce chloride penetration and alkali–silica reaction under suitable conditions [13,18,23,79].

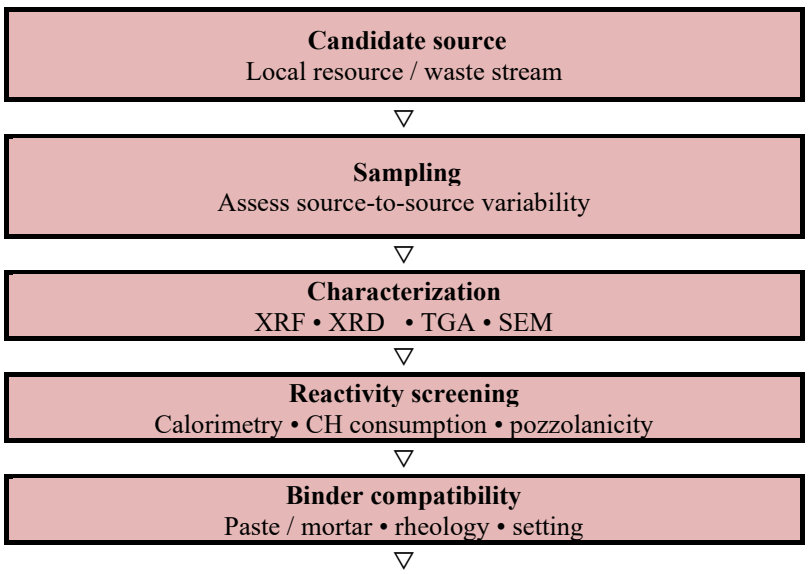
Sulfate resistance is often improved by reducing the amount of reactive clinker phases and modifying hydrate assemblages, although the response depends on sulfate type, SCM chemistry and exposure conditions. Carbonation requires more careful interpretation. SCMs can reduce pore connectivity but also reduce portlandite reserves; therefore, faster carbonation does not necessarily mean poorer overall durability, and the risk to reinforcement must be assessed together with moisture, pore structure and corrosion behavior [42-49,79].

Freeze–thaw performance also depends on air-void system, saturation and curing. The supplied short-term-curing study found that SCM-containing mixtures could suffer reduced early freeze–thaw resistance when curing was insufficient, reinforcing the importance of curing before exposure [75]. This illustrates a general principle: the same SCM can produce different durability outcomes under different curing histories.

X. Multi-Component SCM Systems

The future of clinker reduction is unlikely to depend on one SCM alone. Ternary and multi-component binders can combine materials with complementary reaction rates and chemistry. For example, limestone and calcined clay can compensate for limitations of individual components through synergistic carboaluminate formation and particle packing [42-49]. Combining fly ash with silica fume or slag can balance early strength, later-age strength and durability, although compatibility and sulfate balance must be considered [75].

Particle-size optimization is another important strategy. Different SCMs can be selected to occupy different portions of the particle-size distribution, improving packing while maintaining reactive surface area [22,51-56]. The filler effect may increase clinker hydration at early ages, partially compensating for dilution [52,53,57]. Such optimization suggests that SCM proportioning should be treated as a particle-scale and reaction-scale problem rather than as a simple percentage-replacement exercise. A systematic framework integrating source identification, sampling, characterization, reactivity assessment, binder compatibility, engineering performance, durability, sustainability, and optimization and validation is proposed in Figure 2. The comparative characteristics of major SCMs, including their dominant reaction mechanisms, strength development, workability effects, durability contributions and principal limitations, are summarized in Table 3 to support performance-oriented material selection.



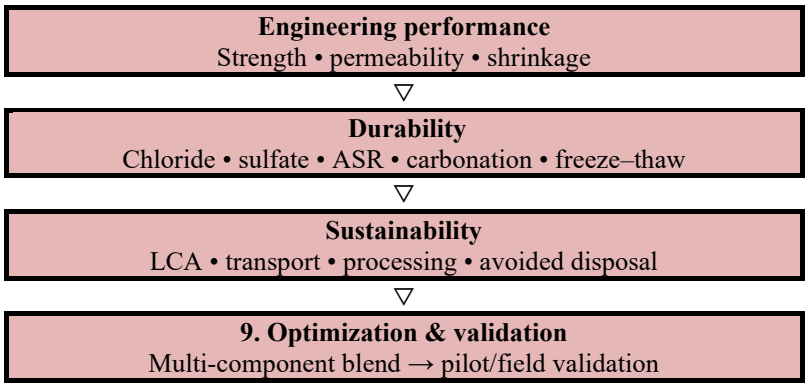


Figure 2. Proposed SCM qualification and mix-design flow chart. [11,16,28–30,63,77–79].

SCM	Main reaction	Early-age strength	Later-age strength	Workability tendency	Key durability contribution	Main concern
Fly ash	Pozzolanic	Often lower	High potential	Often favorable at moderate dosage	Permeability/transport reduction	Slow reaction, supply
GGBFS	Latent hydraulic	Often lower at high dosage	High potential	Often favorable	Chloride/sulfate resistance	Supply and curing
Silica fume	Highly pozzolanic + filler	High	High	Reduced without admixture	Very low permeability	Water demand/agglomeration
Calcined clay	Highly pozzolanic	Moderate–high	High	Increased water demand possible	Refined pore structure	Calcination/process control
Natural zeolite	Pozzolanic + internal water storage	Moderate	High potential	Higher water demand	ASR/chloride benefits	Deposit variability
Pumice/perlite	Pozzolanic + filler	Moderate	Moderate–high	Variable	Reduced transport in optimized systems	Fineness/reactivity
Agricultural ash	Mainly pozzolanic	Variable	Potentially high	Often reduced	Pore refinement when processed	LOI/porosity/variability
Ground glass	Pozzolanic + filler	Moderate	High potential	Variable	Pore refinement	Alkali and particle-size control
Steel slag	Hydraulic/pozzolanic	Variable	Variable–high	Variable	Potential strength/density benefits	Expansion/free CaO–MgO

Table 3. Practical comparison of major SCM groups. [9,13,16-19,20,31-44,63-74,75,79].

XI. Sustainability and Supply-Chain Considerations

The environmental benefit of SCMs is not universal. A by-product with negligible allocated burden may produce a substantial benefit, whereas an SCM requiring intensive drying, grinding, calcination and long-distance transportation may offer a smaller advantage [2-5]. Allocation assumptions in life-cycle assessment can materially change conclusions [2,8]. Therefore, SCM selection

should consider embodied energy, transport distance, processing requirements, avoided disposal and the service life of the resulting concrete.

The depletion or changing availability of traditional SCMs makes diversification strategically important [5,7,16]. New sources can include reclaimed fly ash, natural minerals, calcined clays, agricultural ashes, glass and industrial residues [17,20,37-40,62-74]. However, circularity should not be pursued at the expense of technical reliability. Candidate materials must meet chemical, physical, durability and environmental requirements before large-scale deployment.

XII. Research Gaps and Future Directions

Several research gaps remain. First, there is a need for standardized reactivity protocols capable of screening diverse SCM chemistries rather than only traditional fly ash and slag [11,12,28,77]. Second, mineralogical and chemical variability needs to be incorporated into mixture design and performance prediction. Third, durability assessment should extend beyond short laboratory exposures to coupled carbonation-chloride, sulfate-chloride and wet-dry conditions.

Fourth, more work is needed on low-grade clays, agricultural ashes and industrial residues at pilot and commercial scales [34-40,63-71]. Fifth, digital characterization and data-driven models could link oxide composition, mineralogy, particle size and calorimetry to concrete performance. Sixth, life-cycle assessment should be integrated with technical optimization from the beginning rather than applied after a mix has already been selected [2-5]. Finally, multi-component binders should be optimized for local raw-material availability, climate, curing regime and durability exposure.

XIII. Conclusions

1. SCMs provide a technically established route for reducing clinker content while modifying strength development, pore structure and durability. Their environmental value arises primarily from clinker avoidance and, for many materials, beneficial utilization of industrial or agricultural residues.
2. SCM behavior is governed by composition, mineralogy, amorphous content, fineness, replacement level, curing and pore-solution chemistry. Consequently, SCM type alone is not an adequate predictor of performance
3. Conventional fly ash, slag and silica fume remain important, but changing industrial production patterns make diversification toward calcined clays, natural pozzolans, zeolites and processed wastes increasingly relevant
4. Calcined clays and limestone–calcined-clay systems are particularly promising because they can exploit widely distributed mineral resources and combine pozzolanic, filler and carboaluminate-forming mechanisms.
5. Agricultural ashes and other waste-derived SCMs offer circular-economy opportunities, but controlled combustion, grinding, classification and contaminant management are essential for consistent performance.
6. Reactivity should be evaluated through complementary methods including chemical/mineralogical analysis, calorimetry, thermogravimetry and performance testing rather than a single strength-based criterion.
7. Durability benefits are often associated with pore refinement and modified hydrate assemblages, but carbonation, freeze–thaw and other mechanisms remain strongly dependent on curing, exposure and mixture composition.
8. Future SCM deployment should prioritize locally available, consistently characterized materials and optimized multi-component binders. Performance-based qualification, life-cycle assessment and field validation should be integrated into the same development pathway.

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