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Effect of Natural and Artificial Supplementary Cementitious Materials (SCMs) on the Mechanical and Durability Properties of Precast Concrete Structures: A Review Study

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Abstract

Portland cement production is a major source of CO_2 emissions, posing significant environmental challenges. In this context, the usage of Supplementary Cementitious Materials (SCMs) has gained attention as an effective strategy to lower cement consumption and produce sustainable, high-performance concrete. These materials play a key role in boosting concrete durability and strength by improving microstructure, diminishing porosity, and forming secondary binding phases. Nevertheless, their widespread application in the precast concrete industry—which requires high early strength, suitable setting time, and desirable workability at early ages—faces challenges. Accordingly, this study reviews research on the influence of SCMs, including fly ash, slag, microsilica, natural pozzolans, and metakaolin, on the properties of fresh concrete, early-age characteristics, as well as long-term mechanical behavior and durability. Solutions for mix optimization are inspected, such as multi-component systems, high-range water reducers, and accelerated curing methods including steam curing, to compensate for the decline in early strength. The results from these studies suggest that through careful selection of SCM type, determination of an optimal replacement percentage, and implementation of a suitable curing process, it is possible to generate precast concrete elements. These elements fulfill technical and economic requirements and offer environmental benefits, representing an important step toward sustainable development.

Keywords: Supplementary Cementitious Materials (SCMs), Precast Concrete, Compressive Strength, Tensile Strength, Durability

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1. Introduction

The growing development of infrastructure and the housing sector, along with the progressive need to adhere to environmental considerations while transitioning toward a sustainable industry, has highlighted the role of concrete as the most widely utilized construction material worldwide. However, the production of Portland cement the primary component of concrete is a highly energy-intensive process and substantially contributes to greenhouse gas emissions, especially carbon dioxide, creating serious environmental challenges for the construction sector (Andrew, 2018; He et al., 2019; Nejad et al., 2025). This situation emphasizes the necessity of identifying strategies to lower cement consumption without compromising structural performance.

In this context, the application of Supplementary Cementitious Materials (SCMs) has emerged as an effective and essential strategy for mitigating the environmental impacts of the concrete industry (Malhotra, 1999). These materials, which emanate from industrial by-products such as fly ash and ground granulated blast furnace slag, or from natural sources such as natural pozzolans and metakaolin, play a key role in diminishing greenhouse gas emissions by lowering Portland cement usage. Further, their participation in pozzolanic reactions as well as their ability to refine the microstructure of cement paste result in increased matrix density, lowered porosity, and thus enhanced durability and performance throughout the service life of concrete (Fantilli et al., 2021; Siddika et al., 2021; Li et al., 2022; Ndahirwa et al., 2022; Basavaraj et al., 2023; Liu et al., 2024; Ahmed, 2024; Sathiparan et al., 2024; Sajeev, et al, 2025).

The primary mechanism of SCMs is the pozzolanic reaction, in which the silica and alumina compounds present in these materials react with calcium hydroxide produced along Portland cement hydration, forming secondary C–S–H gel. This secondary gel, which is the main contributor to boosted strength and density, significantly enhances the mechanical properties as well as durability of concrete (Scrivener & Nonat, 2011; Panesar, 2019; Pol Segura et al., 2023). In addition, the physical filler effect of fine SCM particles fills micro-voids within the cementitious matrix, lowering permeability by diminishing porosity and improving cohesion among paste components (Frías & Cabrera, 2000; Hashim & Hamid, 2015; Kumar et al., 2022).

In spite of the clear advantages of SCMs, their widespread use in certain sectors—particularly precast concrete production—confronts challenges. The precast industry requires rapid formwork turnover and high production efficiency; as such, attaining sufficient early strength within a short period, typically 18 to 24 hours, is a fundamental requirement (Nassiri et al., 2025). Since many commonly used SCMs, such as fly ash and slag, present slower hydration rates than Portland cement, their incorporation may delay setting time and lower early-age strength. This conflict between environmental sustainability goals and the technical as well as economic demands of production highlights the need for intelligent management and optimization of SCM usage in precast applications (Naik & Ramme,1990; Ordillas et al.,2025; Kim & Lee, 2025).

Despite these early-age challenges, targeted and optimized application of SCMs has indicated that both durability and environmental performance can be significantly enhanced. Domestic studies support this conclusion; for example, Shoaei et al., (2024) found that partially replacing Portland cement with a combination of blast furnace slag and silica fume can extend the service life of concrete slabs from approximately 12 years to more than 100 years while lowering the carbon footprint by about 35%. These forecasts are based on analytical models of chloride ion penetration that consider environmental chloride concentration, temperature, diffusion coefficients, and microstructural characteristics. Such findings highlight the importance of selecting the appropriate type and dosage of SCMs to design durable as well as sustainable concretes. They also demonstrated that intelligent SCM management can achieve a desirable balance between technical requirements and environmental objectives (Shoaei et al., 2024).

This review article aims to integrate and comprehensively analyze two seemingly distinct domains: the fundamental properties of supplementary cementitious materials and the practical requirements of precast concrete. Accordingly, the study systematically investigates the impacts of various natural and artificial SCMs on fresh concrete properties, early-age behavior (including workability, setting time, and early strength development), and long-term mechanical as well as durability performance. It also scrutinizes practical strategies for mix optimization, including the usage of multi-component systems.

2. Classification and Mechanisms of Action of Supplementary Cementitious Materials

Supplementary Cementitious Materials (SCMs) perform diverse functions in concrete depending on their origin and physicochemical role in the cementitious system. Generally, these materials are categorized into two groups based on origin—natural and industrial—and are classified according to their behavior in the cementitious matrix based on reactive and physical mechanisms. A precise comprehension of these mechanisms not only provides a basis for designing optimal mixes but also makes it possible to predict the performance of concrete at early ages as well as in the long term.

2.1. Pozzolanic Reaction

The pozzolanic reaction is regarded as the most important chemical mechanism in many Supplementary Cementitious Materials (SCMs). Even though a pozzolanic material by itself does not have significant binding properties, in the presence of moisture it reacts with the calcium hydroxide arising from the hydration of Portland cement, producing secondary calcium silicate hydrate (C–S–H) gel. The formation of this additional gel results in the filling of voids, improvement of the microstructure, and enhanced microscopic interlocking, thus leading to a significant enhancement of concrete strength and durability, especially at middle and later ages. The intensity of this process is affected by factors such as the amount of amorphous silica, specific surface area of the particles, curing temperature, and mixing ratio (Setina et al.,2013; Rashad,2013; Ahmad et al.,2022).

Empirical studies also suggest that these same mechanisms can be observed in the natural pozzolans found in Iran. For instance, Abdolshah et al. (2021) noted that replacing about 10% of cement with zeolite and bentonite can improve the compressive and tensile strength of concrete, while higher percentages (around 16%) have a negative impact on mechanical properties. Further, Sharbatdar and Oruhi(2019) reported that the use of zeolite extracted from Semnan mines along with 2% microsilica led greater compressive and flexural strength of concrete by about 10%. These findings suggest that the influence of pozzolans on concrete strength depends on the cement replacement level and the amount of $Ca(OH)_2$available for the pozzolanic reaction; at low percentages, the secondary C–S–H gel formed boosts the strength, but at higher percentages, a shortage of $Ca(OH)_2$ lowers the beneficial effect of the pozzolan.

2.2. Filler Effect

Ultrafine supplementary cementitious materials, such as microsilica or ultrafine fly ash, owing to their small particle size and high specific surface area, are capable of physically filling the pores and voids that exist in the cement paste. This effect, which usually takes place before the onset of pozzolanic reactions, results in diminished effective porosity, decreased permeability, and heightened density of the microstructure. Hence, the ingress of aggressive ions such as chloride and sulfate is limited (Hamada et al., 2023; Li et al., 2022).

2.3. Pozzolanic and Cementitious Activity

Some supplementary cementitious materials, such as blast furnace slag and Class C fly ash, in addition to their pozzolanic behavior, contain activating compounds that enable them to react directly with water. Functionally, these materials fall between a pure pozzolan and a hydraulic cement. Concretes embedding these materials typically achieve high ultimate strength, though their early-age strength development is relatively slower (American Concrete Institute, 2017; Moradikhou et al., 2022).

2.4. Artificial (Industrial) Supplementary Cementitious Materials

Industrial supplementary cementitious materials are primarily obtained from by-products of major industries. Their use, in addition to boosting concrete quality, is considered a sustainable solution for waste management. Fly ash, produced from coal combustion, is classified into two categories: Class F (pozzolanic) and Class C (with cementitious–pozzolanic properties). The spherical shape of its particles ameliorates workability and lowers the water demand of the mix, thereby augmenting concrete fluidity (Wardhono,2018). Ground granulated blast furnace slag, produced through rapid cooling of molten slag followed by grinding, exhibits both cementitious and pozzolanic activity, contributing to enhanced ultimate strength, diminished permeability, and improved chemical durability of concrete (Ohtsuka & Dan, 2019). Alongside these two, microsilica is recognized as the finest commonly used supplementary material, collected from the fumes of ferro-silicon furnaces. Its extremely fine particles, in addition to their physical filler impact, participate in an intense pozzolanic reaction that allows for the development of very high strengths and exceptionally low permeability in concrete. Each of these industrial materials, with its specific characteristics, can hence effectively boost the mechanical properties and durability of concrete (Hamada et al., 2023).

2.5. Natural Supplementary Cementitious Materials

Natural supplementary cementitious materials are directly extracted from mineral sources, and in some cases require processing to activate their pozzolanic properties. Among these materials are volcanic ash, which provides reactive amorphous silica (Huang et al., 2025), and kaolin, which becomes highly pozzolanic post-calcination (Narmatha & Felixkala, 2016). These materials generate strong pozzolanic reactions after activation, resulting in the formation of secondary gels and improvement of the concrete microstructure.

Further, zeolite, with its ion-exchange capacity, and bentonite, through their influence on the rheological behavior of fresh concrete, play important roles in boosting the mechanical properties as well as workability of cementitious mixes (Emam & Yehia, 2017; Dabbaghi et al., 2021). Thus, natural materials—similar to industrial SCMs—can effectively ameliorate various aspects of concrete performance when properly selected and processed.

2.6. Effect of Supplementary Cementitious Materials on Fresh Concrete Properties and Early-Age Strength

Controlling the behavior of concrete in its fresh state and at very early ages—particularly within the first 24 hours—is of utmost importance in various applications, especially in the precast concrete industry where rapid formwork removal and early loading are essential. Supplementary Cementitious Materials (SCMs) can modify the behavior of fresh concrete depending on their particle size, specific surface area, particle geometry, and chemical characteristics, and either accelerate or delay early-age strength development. A precise understanding of these effects is thus necessary for designing optimized mixes in sensitive projects.

Studies suggest that fine materials such as bentonite and microsilica generally augment viscosity and lower the fluidity of fresh concrete; nevertheless, the physical filler impact of their fine particles enhances microstructural density and diminishes permeability. Microsilica, in particular, through its intense pozzolanic reaction, generates very high early-age strengths and significantly decreases concrete permeability (Fode et al., 2023).

In contrast, fly ash and volcanic ash, given their fine particle size and high reactive surface area, not only enhance concrete fluidity but also contribute to hydraulic-pozzolanic activity, boosting compressive and tensile strength at early ages. Their optimal replacement level is typically around 10–20%; higher dosages may heighten viscosity and delay early strength development (Fode et al., 2023).

Natural materials such as kaolin and zeolite, with their pozzolanic activity and high specific surface area, also contribute to augmented early-age strength (7–28 days). Zeolite, in particular, can ameliorate the workability of fresh concrete through ion-exchange mechanisms and modification of paste rheology, enabling faster formwork removal (Nabizadeh Shahrbabak et al., 2017).

Research undertaken at Iran University of Science and Technology indicates that zeolite raises the viscosity and stability of fresh concrete. Although it may slightly lower early-age compressive strength compared to the control mix, the strength at 28 and 90 days equals or exceeds that of the control. This improvement stems from the pozzolanic reaction of zeolite with cement hydrates as well as the filling of fine pores in the matrix. When compared with microsilica at similar replacement levels, zeolite provides better improvements in mix fluidity and stability, while microsilica has a stronger impact on long-term strength. As such, the optimal use of zeolite in concretes produced in Iran can maintain fresh concrete workability while boosting medium- and long-term strength, contributing to diminished cement consumption and supporting sustainability goals (Nabizadeh Shahrbabak et al., 2017).

Overall, the combined findings suggest that selecting the appropriate type and dosage of SCMs can concurrently achieve desirable fresh-state workability and adequate early strength. In precast concrete and other applications where early strength is critical, the correct combination of SCMs plays a pivotal role in fulfilling technical and economic requirements. These results highlight the significance of intelligent mix design and precise control of SCM replacement levels to optimize early-age concrete performance.

2.7. Proposed Strategies for Compensating Early-Age Strength Reduction

In order to overcome the challenge of reduced early strength in concretes containing Supplementary Cementitious Materials (SCMs), several strategies have been identified in previous studies. One key approach is the usage of ternary systems, where two different SCMs—such as fly ash combined with microsilica or slag combined with microsilica—are incorporated for achieving complementary performance. In these systems, microsilica offsets the slower reactivity of fly ash or slag through contributing to higher early strength, while fly ash or slag boost workability, improve long-term strength, and augment durability (Dunstan, 1985; Yehia et al., 2015; Canpolat et al., 2018; Salehi & Mazloom, 2019; Duc et al., 2024; Vagadiya & Vekariya, 2024).

Another effective strategy is lowering the water-to-cementitious materials ratio. Since some SCMs, such as fly ash, have water-reducing effects, the w/cm ratio can be lowered without compromising workability. This reduction directly contributes to enhanced early and ultimate strength (Wang et al., 2016; Sakib et al., 2021).

Accelerated curing is also recognized as an efficient method for compensating early-age strength loss. Techniques such as steam curing or raising the curing temperature significantly augment the rate of hydration and pozzolanic reactions. Even in mixtures containing high proportions of fly ash or slag, accelerated curing can provide the early strength necessary for timely formwork removal. (Atis et al., 2002; Park et al. Park et al.2019; Ozioko & Ohazurike. 2019)

3. Effect of Supplementary Cementitious Materials on the Mechanical Properties and Durability of Hardened Concrete

Beyond the initial ages and upon hardening of concrete, the role of Supplementary Cementitious Materials (SCMs) in heightening mechanical properties and especially improving durability becomes fully evident. At this stage, both chemical mechanisms—primarily the pozzolanic reaction—and physical mechanisms such as fine-particle filling contribute to creation of a denser microstructure with lower porosity and stronger internal bonding. This refinement directly augments the strength (particularly at intermediate and later ages), ameliorates deformation behavior, and significantly boosts durability against aggressive environmental actions such as chloride ion penetration, sulfate attack, freeze–thaw cycles, and carbonation. For these reasons, systematic assessment of the effects of SCM type, dosage, and intrinsic characteristics on durability as well as mechanical performance is essential for designing sustainable, high-quality concrete mixtures (Fode et al., 2023).

3.1. Compressive and Tensile Strength

Compressive strength, as the most widely utilized structural design indicator, is strongly governed by the microstructure and the evolution of hydration products within the cementitious matrix. Experimental results indicate that the incorporation of supplementary cementitious materials such as fly ash and slag generally results in a reduced rate of compressive strength development at early ages (3–7 days), a behavior assigned to their lower initial reactivity compared to Portland cement and the delayed onset of pozzolanic reactions. Nevertheless, as these reactions progress at later ages, the microstructure becomes denser, porosity drops, and matrix cohesion grows, ultimately generating 56- and 90-day strengths equal to or greater than those of the control concrete (Fode et al., 2023).

In contrast, microsilica behaves differently owing to its extremely high specific surface area, ultrafine particle size, and rapid pozzolanic reactivity. These characteristics bring about a significant increase in compressive strength at both early and later ages. The steeper slope of the early-age strength development curve in concretes containing microsilica arises from the combined effect of its physical filler action and the accelerated formation of secondary C–S–H gel (Fode et al., 2023). The impact of SCMs on tensile strength generally follows a trend similar to compressive strength, though with a narrower range of variation. Improvements in the interfacial transition zone and heightened internal cohesion owing to pozzolanic product formation are considered the primary contributors to augmented tensile strength. Studies suggest that concretes containing fly ash can exhibit superior tensile performance compared to control mixes at later ages (Fode et al., 2023).

Peyman et al. (2024) further noted that the combined use of nanosilica and steel fibers can establish a strong synergistic effect in enhancing mechanical properties. Their study ascertained the influence of colloidal nanosilica and reinforcing fibers (steel and polypropylene) on concrete using standard test specimens. They found that increasing the dosage of each fiber type, as well as nanosilica, enhanced compressive, tensile, along with flexural strengths (Figure 1,2) while lowering slump and water absorption. The most significant improvement occurred in a specimen containing 7% steel fibers and 3% colloidal nanosilica, where flexural, compressive, and tensile strengths rose by 54.34%, 35.62%, and 26.31%, respectively, compared to the control. Specimens with 5% steel fibers and 3% nanosilica also presented notable gains in tensile strength, whereas adding 0.4% and 0.7% polypropylene fibers had only a limited effect.

Behavioral analysis revealed that concrete without fibers exhibited brittle failure, while the presence of steel and polypropylene fibers dwindled brittleness and boosted toughness by limiting crack propagation. Further, the specimen containing 3% nanosilica revealed the lowest water absorption (2.1%), representing a 32% reduction relative to the control. These findings suggest that an optimal combination of ultrafine nanosilica and steel fibers not only enhances mechanical performance but also reduces permeability, offering an effective approach for creating strong and durable structural concretes (Peyman et al., 2024).

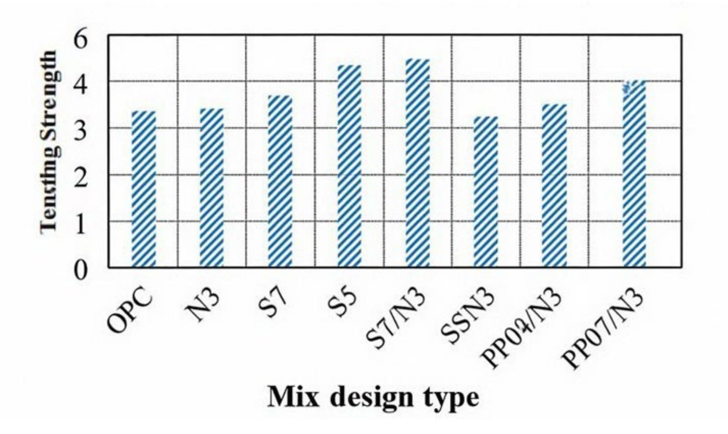

Figure 1. Tensile strength test results reported by Peyman et.al (2024)

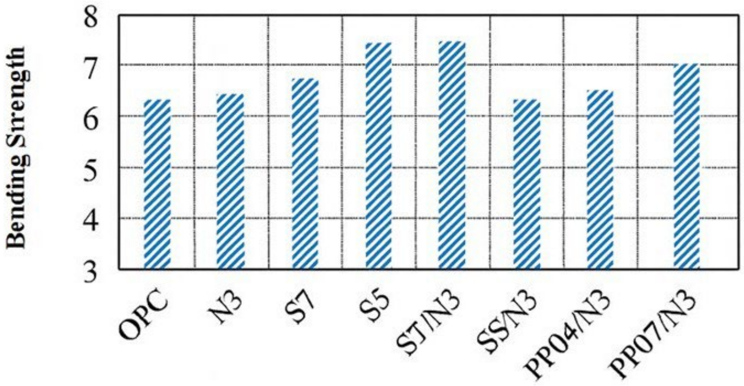

Figure 2. Flexural strength test results reported by Peyman et.al (2024)

3.2. Modulus of Elasticity and Flexural Strength

The mechanical properties of concrete, which determine its stiffness and behavior under loading, are governed primarily by the density and quality of the cementitious matrix as well as the characteristics of the aggregates. The modulus of elasticity is generally less sensitive to supplementary cementitious materials (SCMs) than compressive strength; nevertheless, the formation of a denser microstructure and the decrement of porosity can bring about slight increases in modulus (Fode et al., 2023).

Empirical evidence demonstrates that in normal-strength concretes, replacing cement with siliceous natural pozzolans may cause a slight decline in the modulus of elasticity, whereas in high-strength concrete (HSC), this reduction becomes noticeable only at high replacement levels (above 40%). In ternary systems containing microsilica and fly ash, the modulus of elasticity is typically reported to be comparable to or slightly higher than that of the reference concrete (Canpolat et al., 2018).

Domestic studies support these findings. Abdolshah et al.(2021) indicated that replacing cement with bentonite and zeolite in various proportions significantly influences the modulus of elasticity (Figure3). At early ages (7days), samples without bentonite presented the lowest modulus, while with prolonged curing time, the combination of 16% bentonite and 10% zeolite generated the highest modulus. At 90 days, the greatest growth in modulus and the highest correlation coefficient were observed in samples containing 16% bentonite and 16% zeolite. The average modulus values at 7, 28, and 90 days were reported as 19.04, 21.49, and 24.11GPa, respectively. These results suggest that as compressive strength rises at later ages, the modulus of elasticity also improves, boosting the structural performance of the concrete.

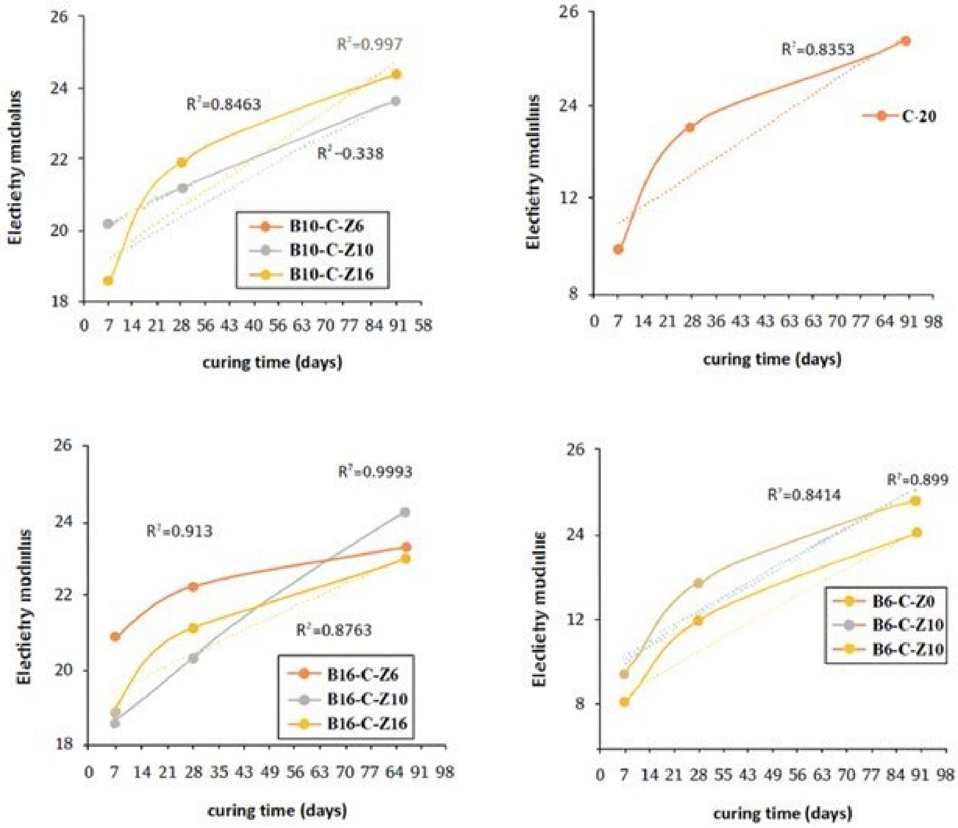

Figure 3. Variations in the modulus of elasticity of concrete containing different percentages of bentonite at various curing ages (Abdolshah et al. 2021)

3.3. Reduction of Permeability and Enhancement of Durability against Chemical Attacks

Perhaps the greatest advantage of applying Supplementary Cementitious Materials (SCMs) is the substantial improvement in durability as well as the extended service life of concrete under aggressive environmental conditions. This improvement is primarily achieved through a marked decrement in the permeability of the cementitious matrix. The physical filler action of fine particles, combined with the formation of secondary C–S–H gel through pozzolanic reactions, curtails both the size and continuity of capillary pores. As a result, permeability to water and ions, as well as capillary absorption, is significantly diminished (Fode et al., 2023; Ndahirwa et al., 2022).

Among all SCMs, microsilica is particularly effective due to its ultrafine particle size, which enables exceptional pore refinement and dramatic reductions in permeability (Fode et al., 2023).

Against sulfate attack, SCMs boost durability through two mechanisms: reducing permeability, which restricts sulfate ingress, and consuming calcium hydroxide along pozzolanic reactions, thereby lowering the availability of reactants required to form expansive products such as ettringite and gypsum. Slag and Class F fly ash are especially effective in this regard.

Resistance to chloride ion penetration—critical for marine structures and reinforced concrete bridges—is also significantly improved. SCMs lessen permeability and disrupt chloride transport pathways, delaying the time required for chloride ions to reach the reinforcement. Further, materials such as slag and zeolite possess chemical adsorption capabilities that allow them to bind chloride ions, further lowering corrosion risk.

Considering carbonation, although SCMs reduce the alkalinity buffer through consuming calcium hydroxide, the notable reduction in permeability slows CO_2 ingress. The overall impact depends on SCM type and dosage; at balanced replacement levels (typically up to 30%), diminished permeability dominates, resulting in a slower carbonation front (Fode et al., 2023).

Recent studies corroborate these conclusions. Baharavar and Esmayili (2024) noted that a combination of 20% microsilica and 2% aluminum oxide reduced water absorption, boosted compressive strength, and provided superior performance in acidic as well as carbonate environments. Mansourghanaei et al. (2023) reported that slag-based geopolymer concrete containing 8% nanosilica and 2% polyolefin fibers exhibited the highest impact resistance along with energy absorption at 300 °C. These findings highlight the effectiveness of innovative combinations—such as nanosilica with fibers—in augmenting concrete performance under thermal and environmental stresses.

4. Optimization of Mix Design for Precast Concrete

The successful application of Supplementary Cementitious Materials (SCMs) in the precast concrete industry, which requires the concurrent achievement of desirable early strength, adequate workability, and long-term durability, entails a systematic and intelligent approach to mix design and optimization. In this regard, a set of key strategies has been proposed, aiming to establish a balance between short-term production requirements and long-term sustainability as well as structural performance goals. This section explores and analyzes these strategies to provide a scientific and practical framework for the effective usage of SCMs in precast concretes.

4.1. Use of Multiple Supplementary Cementitious Material Systems

The use of a single type of Supplementary Cementitious Material (SCM) often necessitates a compromise among the various properties of concrete; thus, a superior solution is to apply ternary systems, in which two different SCMs are used concurrently to compensate for each other's shortcomings and boost the strengths of the combination. One of the most commonly utilized combinations in precast concretes is the system of microsilica along with fly ash or slag. In this system, microsilica, through its rapid pozzolanic reaction as well as exceptional filler effect, provides early strength and significantly lowers concrete permeability, while fly ash or slag ameliorate the workability and stability of the fresh mix, neutralize the water-reducing effect caused by microsilica, and via a long-term pozzolanic reaction, contribute to boosting ultimate strength and enhancing chemical durability. For instance, a common mix could consist of 8 to 10% microsilica along with 15 to 20% fly ash or slag. Another system employed to achieve specific properties is the combination of limestone and calcined clay (metakaolin). Metakaolin, as a highly active pozzolan, heightens the early strength and durability of concrete, while limestone powder, through filling voids and improving workability—in addition to reducing mix cost—also helps accelerate initial setting. This combination can be a suitable option for projects demanding a balance between mechanical performance and economic considerations.

4.2. Role of Fine Materials and Rheology-Modifying Admixtures

Simultaneous management of workability and early-age strength in concrete mixtures containing Supplementary Cementitious Materials (SCMs) often requires the usage of advanced chemical admixtures. High-range water-reducing admixtures—particularly polycarboxylate ether (PCE)–based types—play a key role in this regard. By dispersing cement and SCM particles and establishing steric hindrance between them, these admixtures allow for achieving high workability, even in self-consolidating concrete, with minimal water content. This decline in mixing water directly increases both early and long-term compressive strength (He et al., 2019; Moradikhou et al., 2022).

Viscosity-modifying admixtures (VMAs) also serve an important function in mixtures with high fines content, such as SCC. In such mixes, the risk of segregation and loss of uniformity rises. VMAs boost the stability of the fresh mixture through ameliorating cohesion and preventing bleeding or aggregate settlement, thereby ensuring consistent quality as well as reliable fresh-state performance (Moradikhou et al., 2022).

4.3. Accelerated Curing for Achieving Higher Early-Age Strength

In order to overcome the challenge of slow strength gain in mixes containing slow-reacting supplementary cementitious materials (SCMs) such as fly ash and slag, accelerated curing technologies are considered an essential and highly effective solution. In the precast concrete industry, the most widely utilized method is steam curing, where elevation of the temperature to approximately 60–80 °C in a saturated environment significantly expedites both hydration and pozzolanic reactions (Narmatha & Felixkala, 2016; Ohtsuka & Dan, 2019). Research indicates that this method can provide the compressive strength required for formwork removal (20–25 MPa) in less than 18 hours, even in concretes containing high levels of fly ash (30% or more) (Narmatha & Felixkala, 2016; Vagadiya, 2024). As such, steam curing not only shortens production cycles but also activates a greater share of the latent reactivity of SCMs at early ages.

5. Analysis and Comparison of Results from Previous Studies

A review of results from various studies on the usage of supplementary cementitious materials suggests that employing these additives plays a substantial role in enhancing the mechanical characteristics and durability of concrete. As illustrated in Figure 4, the optimum replacement percentages of various supplementary cementitious materials (SCMs) vary depending on their type. The available data suggest that almost all of these materials, when applied within an appropriate range, improve the behavior of concrete in the short term and especially in the long term through modifying pozzolanic reactions and heightening the density of the microstructure. One of the most prominent patterns observed in the results is the existence of an optimal range for the replacement percentage, which is typically reported to lie within 5-20%. Selection of this value directly depends on the type of material, its pozzolanic activity level, and its fineness. For instance, silica fume usually presents the best performance at lower percentages, such as 7 to 12%, whereas materials like kaolin or fly ash can sometimes be used effectively even up to 30 or 40%.

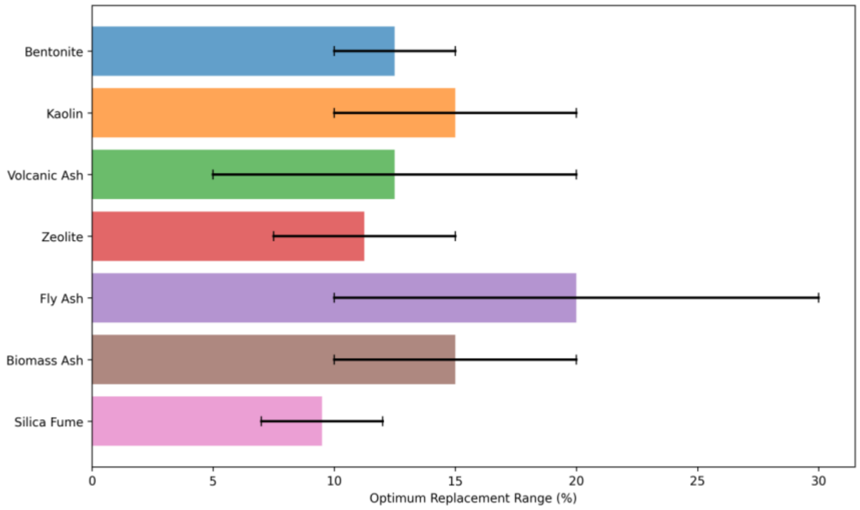

Figure 4. Optimal replacement percentages of supplementary cementitious materials (SCMs)

These differences emanate from variations in mineral structure, reactivity level, and each material's influence on the water-to-cement ratio and the rheology of the mix. Alongside the topic of replacement percentage, examination of the trend of strength development is also very important. Some materials, such as silica fume, cause a significant rise in early strength at 7 and 28 days, while others, including fly ash, bentonite, or zeolite, have slower reactions and present their greatest impact at 56 to 90 days or even later. This behavior emphasizes that appraisal of the true performance of pozzolanic materials based solely on early strength is insufficient, and long-term tests are essential to obtain a complete picture. The curing time of supplementary cementitious materials and their effects on the strength parameters of concrete based on the reviewed studies are also presented in Figures 5 and 6.

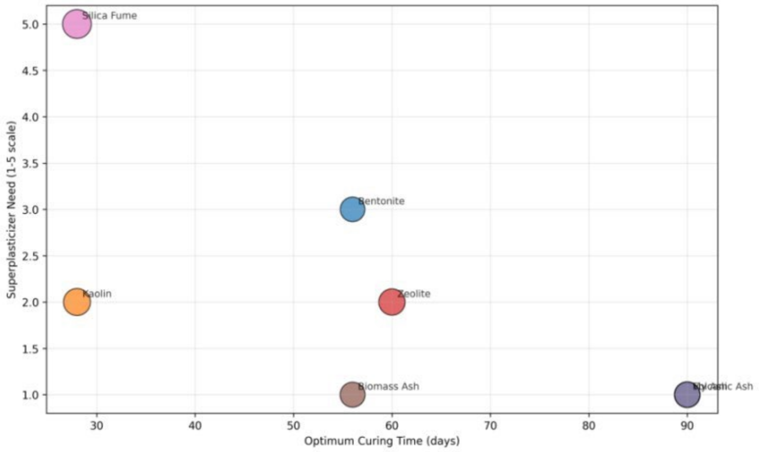

Figure 5. Curing time–dependent behavior of supplementary cementitious materials (SCMs).

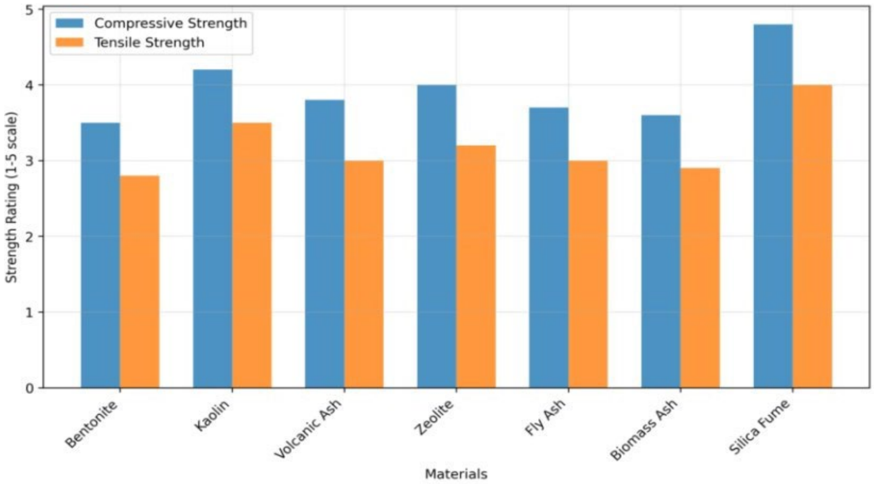

Figure 6. Effect of supplementary cementitious materials (SCMs) on concrete strength parameters

In general, almost all mentioned materials, within their optimal range, at least maintain compressive strength at the level of the control concrete and typically induce a noticeable improvement in compressive, tensile, or flexural strength. The greatest growth in strength usually takes place when a combination of an appropriate replacement percentage and suitable curing conditions is provided. Among the most important common characteristics of these materials is their positive role in boosting concrete durability.

The available results almost uniformly indicate that all these materials, except in cases where they are used in excessive dosages, mitigate the effect of acid attack, which is one of the major challenges for the long-term performance of concrete. This is owing to the reduction of free calcium hydroxide and the increased formation of stable C-S-H gels, which act more resistant in acidic environments. An examination of water absorption also reveals reduced permeability and augmented density of concrete in the presence of materials such as silica fume, zeolite, and kaolin, though for bentonite, due to its swelling behavior, different results have been reported. The effects of each supplementary cementitious material on water absorption and the acid resistance of concrete are also presented in Figure 7.

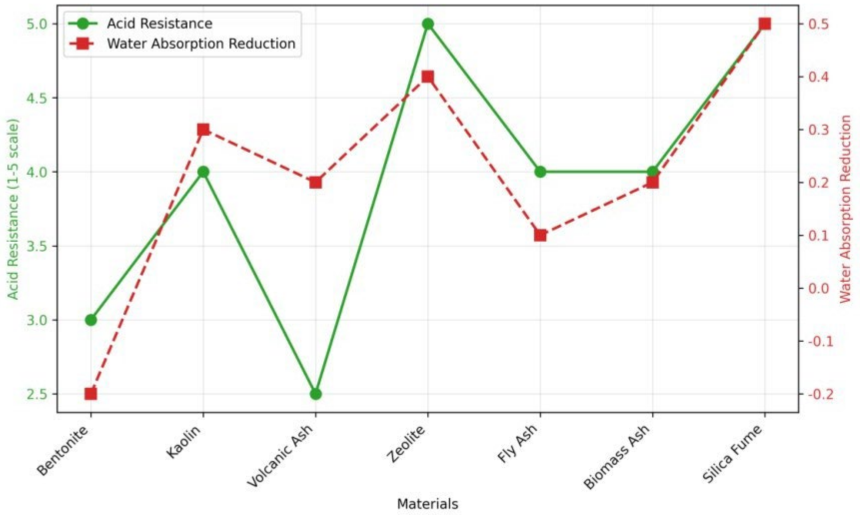

Figure 7. Effect of supplementary cementitious materials (SCMs) on water absorption and acid resistance of concrete

Diminished water absorption directly results in lowered ingress of aggressive ions as well as improved concrete performance under various environmental cycles. In cases such as silica fume or biomass ash, this property is very pronounced owing to their high fineness and specific surface area. In spite of these advantages, the impact of these materials on the water-to-cement ratio and the need for plasticizers must also be considered. Some of them, such as bentonite or silica fume, due to their very fine structure, may require greater amounts of plasticizer to maintain desirable workability and slump. Accordingly, in actual mix designs, selecting an appropriate replacement percentage should be accompanied by adjusting plasticizer dosages as well as inspecting the precise material composition. Given the high sensitivity of some materials to their source, particle size distribution, and chemical composition, undertaking preliminary tests for each project is essential.

The provided radar chart enables the concurrent comparison of three selected supplementary materials—bentonite, zeolite, and silica fume—based on six key performance indicators: compressive strength, tensile strength, acid resistance, reduced water absorption, workability related to curing time, and the required amount of plasticizer. Through plotting the performance profile of each material, this chart clearly reveals the relative differences between them in terms of the balance or imbalance among the indicators. According to the data used in this chart, silica fume scores high on the axes related to mechanical strength and lowered permeability but simultaneously perform more poorly on the indicator related to plasticizer demand.

This characteristic indicates that while using silica fume results in a noticeable enhancement in strength and microstructural density, it entails a higher consumption of water-reducing admixtures to maintain the workability of fresh concrete. In contrast, the plotted profile for zeolite exhibits a relatively balanced behavior across all mechanical and durability axes. Zeolite performs well on the acid resistance indicator and does not show significant decline in the other indicators. Further, its required plasticizer amount is less than that of silica fume, which can be regarded as an execution advantage. This pattern reveals that zeolite can be a suitable option for applications where attaining several performance indicators simultaneously at an acceptable level is important. The profile of bentonite, according to the plotted data, presents more dispersion than the other two materials, and its values for mechanical and durability indicators are mainly within the average range. Nevertheless, no severe drop is observed on the plasticizer demand axis, which can be an advantage under certain execution conditions. Overall, in this comparison, bentonite is a material with a milder effect, and its selection may depend more on factors such as availability, cost, or specific mixing conditions.

Comparison of these three materials in a single chart highlights the concept of performance trade-off; means that a significant rise in one indicator may lead to a relative decrease in another. Thus, appraisal of the superiority of a material based solely on maximizing a few indicators is insufficient, and a simultaneous analysis of each material's weaknesses is also necessary. This review demonstrates that the final selection of a supplementary material should be based upon the functional priorities of the project: silica fume is suitable for projects where achieving very high strength and density is the priority; zeolite is more appropriate for applications requiring balanced and stable performance across several different indicators; and bentonite can be utilized for projects that need an economical option with average performance. Figure8 presents a comparative evaluation of the effects of bentonite, zeolite, and silica fume on the key performance indicators of concrete.

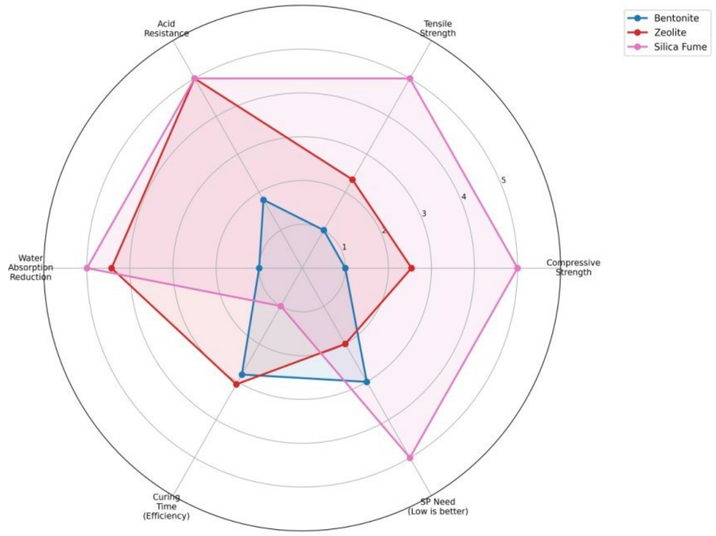

Figure 8. Comparative analysis of performance indicators of bentonite, zeolite, and silica fume

Table 1 outlines a comparative summary of the various materials, highlighting their differences and commonalities in a concise and comparable manner. These findings reveal that selection of the type and quantity of supplementary material needs to be made according to the project's objective, environmental conditions, and performance requirements. If the goal is to enhance early strength, silica fume is the best option; however, if the goal is long-term durability and diminished permeability at a suitable cost, materials such as kaolin, zeolite, or fly ash offer more desirable performance.

On the other hand, biomass ash is a sustainable and environmentally friendly option that can serve as a suitable alternative in green projects. In spite of the provision of general patterns, owing to differences in the source of natural materials such as zeolite and bentonite, as well as the high sensitivity of the mix design to the water-to-cement ratio, performing project-specific tests is essential to determine the optimal combination and replacement range.

Table 1. Comparison of supplementary cementitious materials based on mechanical performance and durability

Material	Optimal replacement range	Overall mechanical behavior	Effect on durability	Key remarks
Bentonite	10–15%	Strength improvement at later ages	Variable results in water absorption; improved acid resistance	Performance varies depending on material type and source
Kaolin	10–20%	Strength enhancement; strong pozzolanic activity	Reduced water absorption and improved acid resistance	Suitable option for high-durability applications
Volcanic ash	5–20%	Increased late-age strength	Reduced water absorption	Behavior similar to fly ash
Zeolite	7.5–15%	Improved medium- and long-term strength	Reduced water absorption; enhanced acid resistance	High ion-exchange capacity; good stability
Fly ash	10–30%	Improved long-term strength	Reduced susceptibility to acid attack	Economical; low heat of hydration
Biomass ash	10–20%	Similar to fly ash	Reduced water absorption and improved acid resistance	Sustainable and environmentally friendly option
Silica fume	7–12%	Highest increase in early-age strength	Significant reduction in water absorption;	Most active pozzolan; high superplasticizer demand

		enhanced acid resistance

6. Conclusion

The review and comparison of the results obtained from research and studies concerning the effects of Supplementary Cementitious Materials (SCMs) on the durability and mechanical properties of concrete structures suggested that the usage of these materials can significantly enhance the technical characteristics and durability of concrete. Studies have indicated that both natural and artificial supplementary cementitious materials positively impact compressive strength, tensile strength, and durability, resulting in improved properties and performance of concrete structures. In addition, these materials, in addition to lowering cement consumption and production costs, can reduce permeability by filling concrete pores and boost its resistance to acidic and other chemical attacks. Thus, partially replacing cement with supplementary cementitious materials not only enhances the mechanical properties of concrete but is also effective on mitigating environmental pollution from cement production and lowering energy consumption. Accordingly, the findings from the conducted research indicate that:

(1) Natural supplementary cementitious materials can replace a greater proportion of cement compared with artificial ones, thereby contributing to the improvement of the mechanical properties of concrete structures while lowering energy consumption and environmental pollution.

(2) The usage of both artificial and natural supplementary cementitious materials (SCMs) can significantly boost the durability properties of concrete materials. Further, use of these materials can reduce water absorption and augment concrete resistance to acidic substances.

(3) Partial replacement with bentonite, biomass ash, and kaolin at 15% and volcanic ash at 20% in the concrete mix can offer the best compressive and tensile strength. Additionally, adding fly ash and zeolite at 10% each to concrete separately achieves the best compressive and tensile strength.

(4) In constructing precast concrete structures with high durability, usage of kaolin, zeolite, or fly ash as supplementary cementitious materials (SCMs) in combination with the cement utilized for concrete provides more desirable performance for the concrete structure.

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