Research on Engineering Structures & Materials
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Review Article

The effects of temperature on the durability of concrete incorporating supplementary cementitious materials (SCMs)

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Article Info

Article History:

Received 08 Mar 2026

Accepted 27 July 2026

Keywords:

Concrete;
Durability;
Slag;
Fly ash;
Silica fume;
Sustainability

Abstract

The durability of concrete incorporating supplementary cementitious materials (SCMs) is strongly influenced by curing and service temperatures, which affect hydration kinetics, microstructural development, and resistance to deterioration mechanisms. Although numerous studies have investigated individual SCMs, a comprehensive comparison of their temperature-dependent performance remains limited. This systematic literature review evaluates the influence of temperature on the mechanical, durability, microstructural, and sustainability performance of concrete containing fly ash, silica fume, ground granulated blast-furnace slag (GGBFS), and metakaolin. A systematic search was conducted using Scopus, Web of Science, ScienceDirect, and Google Scholar databases, and relevant studies were screened according to predefined inclusion and quality-assessment criteria. The reviewed evidence indicates that silica fume and metakaolin exhibit optimal performance at moderate temperatures (20–40 °C), increasing compressive strength by approximately 20–30% and reducing chloride migration coefficients by up to 60%. Fly ash shows enhanced effectiveness at moderately elevated temperatures (40–60 °C) due to thermal activation of its pozzolanic reactions, while GGBFS demonstrates stable performance across a broader temperature range. Temperatures exceeding 60 °C accelerate hydration but promote pore connectivity, interfacial transition zone degradation, and thermally induced microcracking, resulting in reduced long-term durability. The findings demonstrate that SCM selection should be adapted to expected thermal conditions and highlight the importance of incorporating temperature as a key parameter in durability-oriented mix design. Furthermore, SCM utilization contributes to clinker reduction and lower CO_2 emissions, supporting sustainable and circular-economy-oriented concrete production.

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1. Introduction

Globally, concrete stands as one of the most widely used construction materials. Its production exceeds ten billion tons annually, underpinning modern infrastructure and supporting global development [1]. The durability of concrete is a critical factor in civil engineering, as it directly influences maintenance costs, service life, and structural performance. Over time, deterioration increases repair demands and structural interventions, imposing significant economic burdens on society [2].

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DOI: http://dx.doi.org/10.17515/resm2026-1556ma0308rv

In this context, the incorporation of mineral additions such as fly ash, silica fume, ground granulated blast-furnace slag (GGBFS), metakaolin, and natural pozzolans has become an effective strategy to enhance both the durability and mechanical properties of concrete [3,4]. The use of these materials not only contributes to sustainability objectives but also significantly modifies the rheological, mechanical, and durability-related behavior of cementitious systems [5].

Supplementary cementitious materials (SCMs) participate in pozzolanic reactions that consume calcium hydroxide produced during Portland cement hydration, leading to the formation of additional calcium–silicate–hydrate (C–S–H) gels. These reactions densify the microstructure and reduce permeability [6]. However, the performance of such blended systems is strongly influenced by temperature during both the hydration process and the service life of the structure [7].

1.1 Mechanisms of Mineral Additions

Mineral additions can be classified according to their chemical nature and mechanism of action. Class F fly ash and silica fume are pozzolanic materials that react with calcium hydroxide in the presence of water to form additional hydrated calcium silicates [8]. Granulated blast-furnace slag, when activated—particularly at elevated temperatures—exhibits both pozzolanic and latent hydraulic properties that contribute to strength development [9,10].

Metakaolin, an artificial pozzolan obtained through the calcination of kaolinitic clays, shows high reactivity due to its fine particle size and large specific surface area [11]. The effectiveness of these materials depends on several parameters, including particle size, chemical composition, specific surface area, and curing temperature. Each material exhibits distinct thermal responses, which govern its influence on durability and mechanical performance under different environmental conditions [12,13].

1.2 Hydration: Effects of Temperature

Among the various factors influencing the behavior of concrete with mineral additions, temperature plays a decisive role in controlling hydration kinetics, microstructural development, permeability, and resistance to deterioration mechanisms [14]. During early hydration, elevated temperatures accelerate chemical reactions and promote rapid precipitation of hydration products. Although this leads to faster strength gain, it often results in a coarser and more porous microstructure, potentially reducing long-term durability [15,16].

The so-called crossover effect is commonly observed in concrete cured at high temperatures. This phenomenon is characterized by higher early-age strength but lower long-term strength compared to concrete cured under moderate temperature conditions [1,3]. This behavior is associated with microstructural heterogeneity and increased porosity [17,18].

1.3 Behavior of Different Mineral Additions

The performance of SCM-modified concrete varies according to the thermal sensitivity of each material. Silica fume, characterized by its extremely high fineness (15,000–25,000 m^2/kg) and high amorphous silica content, exhibits high reactivity at moderate temperatures (20–40 °C) [19]. While it significantly reduces permeability under these conditions, its effectiveness decreases at temperatures above approximately 60 °C due to microstructural coarsening and thermal microcracking [20,21].

In contrast, Class F fly ash requires higher curing temperatures to fully activate its pozzolanic potential due to its relatively low intrinsic reactivity. Studies indicate that its contribution to strength increases significantly when curing occurs between 40 °C and 60 °C [18]. However, excessively high temperatures may trigger premature reactions and lead to a non-uniform distribution of hydration products [22,23].

GGBFS presents intermediate thermal sensitivity and can be effectively activated over a wider temperature range. Its latent hydraulic behavior contributes to both early- and long-term strength, making it less sensitive to adverse thermal effects compared to other mineral additions [24].

1.4 Exposure Conditions and Durability

During the service life of concrete structures, thermal stresses can induce internal fluctuations that promote interfacial microcracking and changes in permeability. These effects become more significant under harsh environmental conditions, such as freeze–thaw cycles, high humidity, or aggressive industrial exposure [21]. The incorporation of mineral admixtures can modify this response, either mitigating or amplifying deterioration depending on the type, dosage, and exposure conditions [7,8].

Temperature variations also accelerate degradation mechanisms, including carbonation, chloride ingress, sulfate attack, and alkali–silica reaction [25]. Although higher temperatures tend to increase the rate of these processes, mineral additions can counteract them by refining the pore structure, consuming calcium hydroxide, and altering the pore solution chemistry [26,27].

1.5 Design and Construction Implications

The thermal behavior of concrete significantly influences the performance of mineral additions and should therefore be considered in mixture design, particularly in structures exposed to aggressive environments [28]. A proper understanding of these interactions is essential for developing durable and sustainable concretes, as well as for improving predictive models used in structural design [29].

In this context, predictive modeling of temperature effects can lead to more efficient and rational design strategies [12]. The objective of this study is to analyze how temperature influences the performance of concrete with mineral additions and to provide guidelines for optimizing the selection and dosage of these materials under specific thermal conditions, thereby enhancing both durability and sustainability [12,23,29].

Acknowledging the influence of temperature during design also requires careful consideration of construction practices and curing methods. For instance, steam curing—commonly used in precast concrete production to accelerate strength development—may introduce microstructural weaknesses that become evident over long-term service conditions [30]. Similarly, inadequate curing in hot climates can lead to plastic shrinkage cracking and thermal gradients that adversely affect surface quality and durability [31].

Therefore, integrating temperature-sensitive durability models into design guidelines would significantly improve structural performance by linking curing conditions, hydration processes, and long-term microstructural evolution [32-35].

Despite extensive research on supplementary cementitious materials (SCMs), important knowledge gaps remain regarding their temperature-dependent performance. Previous studies have predominantly focused on individual SCMs, such as fly ash, silica fume, GGBFS, or metakaolin, and have generally evaluated either mechanical properties or durability indicators within limited temperature ranges. Furthermore, most investigations have concentrated on curing temperature effects, while the combined influence of curing and service temperatures on long-term performance has received comparatively less attention. Existing reviews also provide limited comparative analysis of different SCMs under varying thermal regimes and rarely integrate mechanical behavior, chloride resistance, sulfate resistance, microstructural evolution, and sustainability considerations within a unified framework. Therefore, a comprehensive synthesis of the mechanisms governing the temperature-dependent durability of concrete incorporating SCMs remains lacking. This study addresses this gap by providing a comparative assessment of major SCM types under different thermal conditions, linking mechanical performance, durability behavior, microstructural mechanisms, and sustainability aspects to support temperature-adapted concrete design strategies [36,37].

Therefore, the novelty of this study lies in providing a comprehensive comparative synthesis of the temperature-dependent behavior of concrete incorporating different supplementary cementitious materials (SCMs), including fly ash, silica fume, ground granulated blast-furnace slag (GGBFS), and metakaolin. Unlike previous reviews, which generally focus on individual SCMs or specific performance indicators, this study compares the influence of both curing and service temperatures

on mechanical properties, chloride resistance, sulfate resistance, microstructural evolution, and sustainability-related performance within a unified framework. This integrated approach enables the identification of common trends, material-specific responses, and key mechanisms governing temperature-dependent durability.

The main objective of this study is to evaluate how temperature affects the performance of concrete incorporating SCMs by identifying the relationships between thermal conditions, strength development, durability indicators, and microstructural changes. The study aims to determine the optimal temperature ranges and SCM types for improving long-term durability and to support the development of reliable, temperature-adapted mix design strategies for practical engineering applications.

2. Materials and Methods

2.1 Literature Selection Criteria

This study was conducted as a systematic literature review (SLR) aimed at evaluating the influence of temperature on the durability and performance of concrete incorporating supplementary cementitious materials (SCMs). The review methodology was designed to ensure transparency, reproducibility, and scientific rigor through a structured process that included literature identification, screening, eligibility assessment, quality appraisal, data extraction, and evidence synthesis.

Relevant studies were identified through a systematic search of major scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar. Predefined inclusion and exclusion criteria were applied to select studies addressing the effects of curing and service temperatures on the mechanical properties, durability performance, and microstructural evolution of concrete containing SCMs. Subsequently, the selected studies were subjected to a quality assessment procedure and the extracted data were synthesized through a comparative analysis of the reported findings.

2.2 Search Strategy

The literature search was conducted between January and February 2026 using four major scientific databases: Scopus, ScienceDirect, Web of Science, and Google Scholar. A structured search strategy was applied to identify studies investigating the influence of temperature on the performance and durability of concrete incorporating supplementary cementitious materials (SCMs).

The search process consisted of three stages: (i) identification of relevant keywords and search terms, (ii) database-specific searches using Boolean operators (AND, OR), and (iii) screening of titles, abstracts, and full texts according to predefined inclusion and exclusion criteria. The following keywords were applied: “concrete durability,” “temperature effects,” “supplementary cementitious materials,” “fly ash,” “silica fume,” “slag,” and “metakaolin.” To ensure the relevance and quality of the collected literature, only peer-reviewed publications written in English were considered. Reference lists of key publications were also manually examined to identify additional relevant studies.

Preference was given to studies published between 2005 and 2025, a period during which research on temperature effects and SCMs has significantly expanded. However, foundational and classical references were also included when necessary to support the theoretical background and interpretation of the reviewed findings.

The final search was completed on 15 February 2026, and the collected records were subsequently screened and evaluated following the systematic review protocol described in this study. The literature search was carried out using major academic databases.

2.2.1 Search Strings

Database-specific search strings were developed using Boolean operators and keyword combinations related to supplementary cementitious materials (SCMs), temperature conditions,

and durability performance. For Scopus and Web of Science, the following search string was applied:

- (TITLE-ABS-KEY ("supplementary cementitious materials" OR "fly ash" OR "silica fume" OR "ground granulated blast furnace slag" OR GGBFS OR metakaolin))
  AND
- (TITLE-ABS-KEY ("temperature" OR "thermal effects" OR "curing temperature" OR "service temperature"))
  AND
- (TITLE-ABS-KEY ("durability" OR "compressive strength" OR "chloride ingress" OR "chloride migration" OR "sulfate attack" OR "microstructure"))

For ScienceDirect and Google Scholar, equivalent keyword combinations were used, including:

- ("supplementary cementitious materials" AND temperature AND durability)
- ("fly ash" OR "silica fume" OR GGBFS OR metakaolin) AND ("curing temperature" OR "thermal exposure") AND ("compressive strength" OR "chloride resistance" OR "sulfate resistance")

Additional searches were performed using alternative terms and reference-list screening to identify relevant studies that may not have been captured through the primary database searches.

2.2.2 Quality Appraisal

The quality of the selected studies was assessed using a structured scoring system based on four evaluation criteria:

- Experimental methodology,
- Clarity and completeness of reported results,
- Consistency with existing literature,
- Relevance to the objectives of this review.

Each criterion was assigned a score ranging from 0 to 2, where 0 indicated poor quality, 1 indicated moderate quality, and 2 indicated high quality. The maximum possible score was 8 points. Studies scoring 6–8 points were classified as high quality, 4–5 points as moderate quality, and below 4 points as low quality. Low-quality studies were excluded from the final synthesis, whereas moderate- and high-quality studies were retained for analysis. The quality appraisal results were incorporated into the evidence synthesis by assigning greater weight to findings reported in high-quality studies. The evaluation criteria, scoring scale, and quality classification adopted for the assessment of the selected studies are presented in Table 1.

Table 1. Quality assessment framework applied to the selected studies

Criterion	Score
Experimental methodology	0–2
Clarity of results	0–2
Consistency with literature	0–2
Relevance to review objectives	0–2
Maximum score = 8	

2.3 Inclusion and Exclusion Criteria

2.3.1 Inclusion criteria

The following types of studies were included:

- Studies evaluating the influence of temperature on mechanical strength, permeability, carbonation, chloride ingress, or sulfate attack in concrete.
- Research analyzing the performance of mineral admixtures such as fly ash, silica fume, GGBFS, and metakaolin.

- Articles presenting validated experimental results or comprehensive review studies in the field.

2.3.2. Exclusion criteria

The following publications were excluded:

- Studies lacking sufficient methodological detail or experimental design description.
- Studies outside the scope of this research, such as concretes without mineral additions or those focused on unrelated deterioration mechanisms.

2.4 Analysis Process

The selected studies were systematically compared and synthesized according to the following criteria:

- Type and physicochemical properties of the mineral admixture.
- Curing temperature and exposure conditions.
- Reported effects on mechanical performance and durability indicators.
- Theoretical approaches or predictive models proposed in the literature.

The reliability of the extracted data was verified through cross-comparison between experimental studies and review papers, ensuring consistency and reproducibility of the research findings. Quantitative data reported in this study were systematically extracted from the selected publications using a standardized data collection procedure. For each study, the following information was recorded: SCM type and replacement level, curing and service temperatures, compressive strength, chloride migration coefficient, sulfate expansion, porosity, microstructural observations, and reported CO_2 reduction indicators.

To facilitate comparison among studies, data were grouped according to SCM type (fly ash, silica fume, GGBFS, and metakaolin) and temperature range. When multiple studies reported similar parameters under comparable experimental conditions, ranges and average values were calculated and reported to provide representative trends. Individual results showing significant deviations from the overall trend were examined and interpreted in the context of differences in mixture composition, testing methods, and exposure conditions.

Data synthesis was performed through a comparative analysis aimed at identifying recurring patterns, agreements, and discrepancies among the reviewed studies. Quantitative values presented in tables and figures therefore represent either ranges, average values derived from multiple studies, or synthesized trends obtained from the literature, as indicated in the corresponding captions. In cases where statistical analyses, such as ANOVA, were discussed, the results were reported directly from the original studies and interpreted within their respective experimental contexts to ensure consistency with the source data. Quantitative data reported in this study were extracted from selected publications.

2.4.1 Information Processing

The collected data were organized into comparative tables and graphical representations, following standard formatting guidelines. This approach enabled the identification of trends, discrepancies, and existing research gaps. This approach ensures that the review process is transparent, systematic, and reproducible, allowing other researchers to replicate the study. The screening process was conducted by reviewing titles, abstracts, and full-text articles to ensure compliance with the defined inclusion criteria.

Figure 1 illustrates the systematic literature review process, including the stages of identification, screening, eligibility assessment, and final study selection. The numbers of records identified, screened, excluded, assessed for eligibility, and finally included are reported to ensure transparency and reproducibility of the review process. All references were selected from peer-reviewed sources and updated to reflect recent developments in the field. Reasons for exclusion during the screening and eligibility stages were documented and considered in the final study selection procedure.

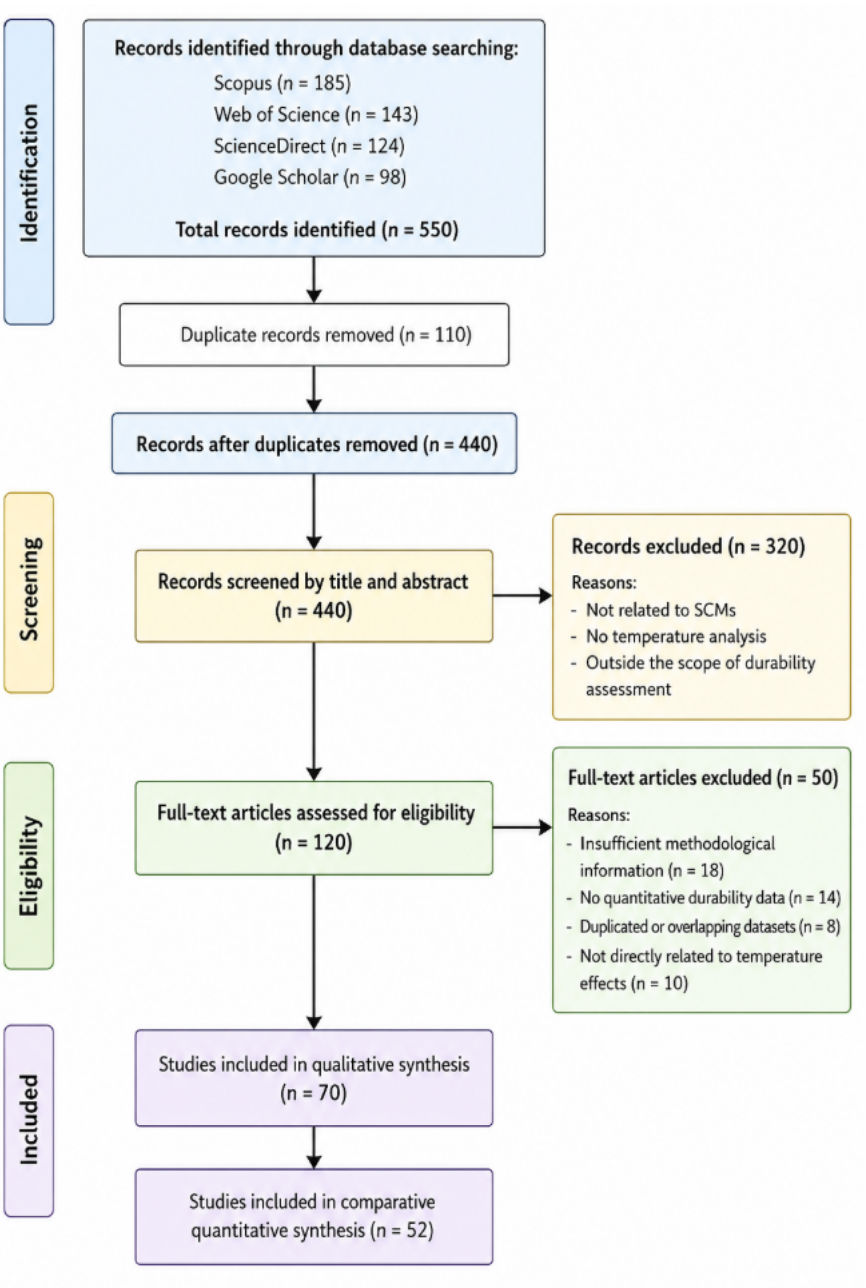


Fig. 1. Flow diagram of the literature review process

3. Results

The reported values presented in this section were synthesized from the selected studies and do not represent a single experimental dataset. Depending on data availability, the reported results correspond to: (i) ranges derived from multiple studies reporting comparable parameters under similar conditions, (ii) average values calculated from groups of studies with consistent experimental variables, (iii) individual values directly extracted from representative studies when limited data were available, or (iv) narrative synthesis of qualitative findings where quantitative comparison was not feasible.

For each parameter, including compressive strength, chloride migration coefficient, sulfate expansion, porosity, and CO_2 reduction, the basis of the reported values is specified in the corresponding text, tables, or figure captions. This approach was adopted to ensure transparency in data interpretation and to facilitate comparison among different SCM types and temperature conditions.

3.1 Mechanical Strength

Several studies have reported that the compressive strength of concrete incorporating mineral additions increases progressively with curing time. Research on silica fume indicates that an incorporation of approximately 10% by weight enhances 28-day compressive strength by about 20–25% compared to control mixtures [38]. In contrast, concrete containing 35% fly ash typically exhibits delayed strength development at early ages; however, after 90 days, it often surpasses the compressive strength of conventional mixes [39-40]. Among the evaluated supplementary materials, metakaolin at a dosage of approximately 15% provides a favorable balance between early-age strength development and long-term performance [41] (see Figure 2).

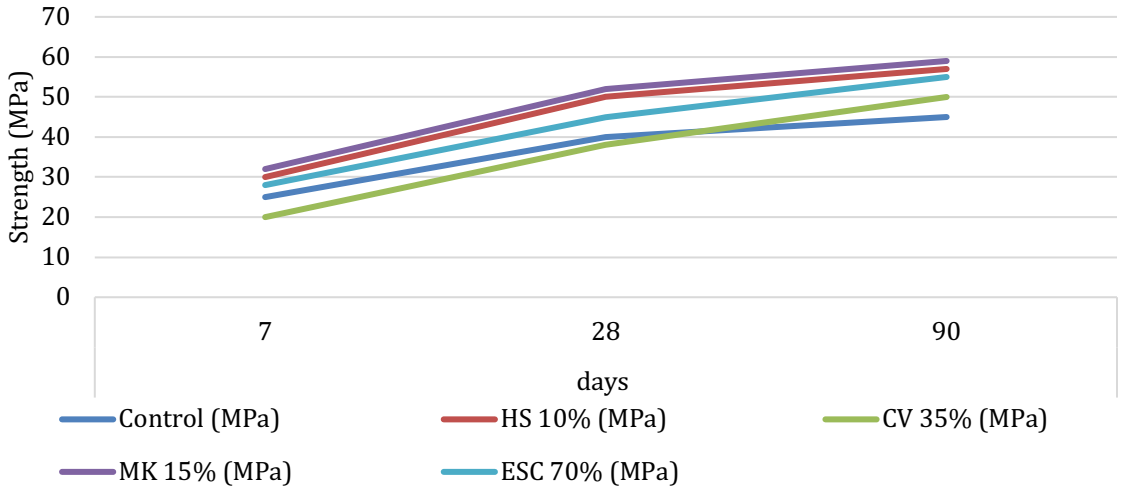


Fig. 2. Evolution of compressive strength (MPa) of concrete incorporating different mineral additions as a function of curing time. Values represent ranges reported in the selected studies [21,23]

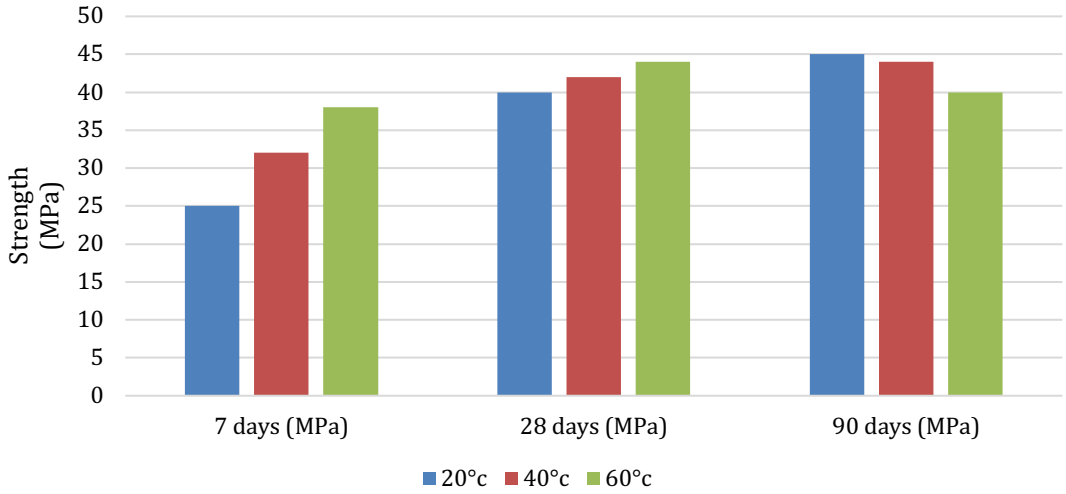


Fig. 3. Effect of curing temperature (°C) on compressive strength development (MPa) of concrete incorporating SCMs. Values represent synthesized ranges obtained from six reviewed studies reporting compressive strength under curing temperatures of 20 °C, 40 °C, and 60 °C. The figure illustrates literature-based trends and does not represent data from a single experimental dataset [24,25].

A quantitative comparison based on the findings of selected experimental studies [38–41] shows that a 10% replacement with silica fume increases 28-day compressive strength by approximately 22–25% relative to control mixtures. This range was identified from six studies reporting comparable replacement levels and curing conditions. Metakaolin at a replacement level of

approximately 15% provides even greater improvements, reaching strength increases of up to 30% relative to conventional concrete mixtures. In contrast, mixtures incorporating approximately 35% fly ash generally exhibit lower early-age strength, with reductions of about 10% at 7 days compared with control mixes. However, based on five reviewed studies, these mixtures exceeded the compressive strength of conventional concrete by approximately 15% after 90 days due to the continued development of pozzolanic reactions.

The reported percentages represent ranges synthesized from studies with comparable SCM contents and curing conditions and were calculated relative to the corresponding control mixtures reported in the original investigations. Regarding temperature effects, increasing curing temperature accelerates early strength development. However, when temperature approaches 60 °C, a reduction in long-term strength is observed [42-44]. Under cyclic thermal conditions (20–60 °C), compressive strength is slightly lower than under isothermal curing at 20 °C (see Figure 3). At approximately 60 °C, early-age strength increases by about 18–22%, while long-term strength decreases by approximately 10–15%.

3.2 Durability Performance

3.2.1 Chloride Penetration

Accelerated migration tests (NT BUILD 492) reported in the reviewed literature [22,23,45] indicate that mixtures containing silica fume and metakaolin reduce the chloride migration coefficient by approximately 40–60% relative to control concretes. These values represent a synthesized range derived from multiple studies with comparable SCM replacement levels and exposure conditions rather than the findings of a single experimental investigation.

Specimens cured at elevated temperatures (approximately 60 °C) generally exhibit increased chloride ingress due to thermally induced microstructural changes, including higher pore connectivity and the development of microcracks, which facilitate the penetration of aggressive agents [29,32]. Among the evaluated SCMs, GGBFS demonstrates intermediate performance, contributing to a more refined pore structure and more uniform chloride concentration profiles. As a result, slag-containing mixtures generally show lower chloride penetration than conventional concrete, although their effectiveness may diminish under prolonged exposure to elevated temperatures (see Figure 4). Silica fume and metakaolin reduce the chloride migration coefficient by approximately 55–60%, whereas curing at 60 °C, chloride ingress may increase by approximately 20–25%.

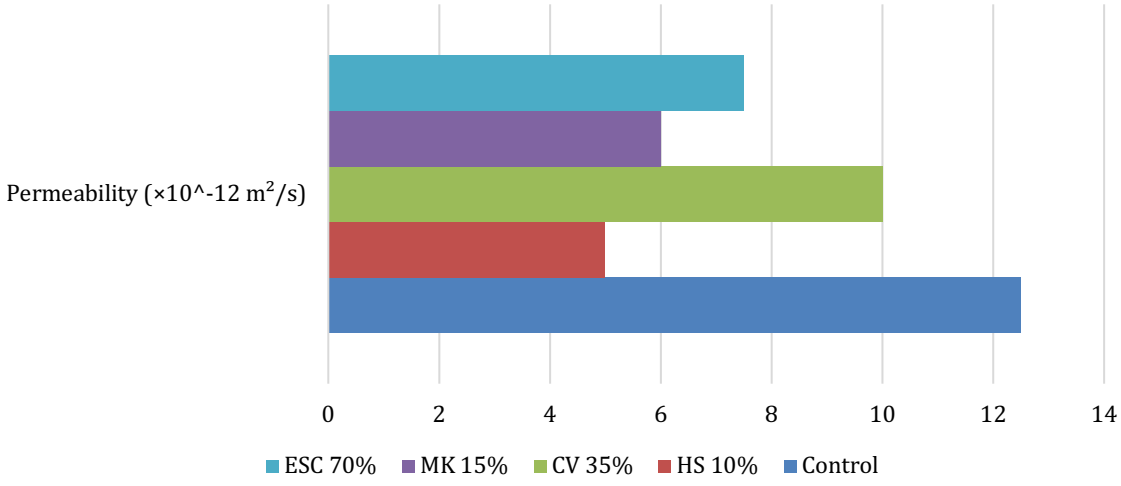


Fig. 4. Variation of the chloride migration coefficient ($\times 10^{-12}$ m^2/s) according to mineral addition. Values correspond to ranges reported in the literature [16, 17]

3.2.2 Sulfate Resistance

Under curing at approximately 20 °C and 12 months of immersion in sulfate solution, conventional concrete without mineral additions exhibits expansions exceeding 0.15%, along with surface degradation and mass loss [1] (see Figure 5).

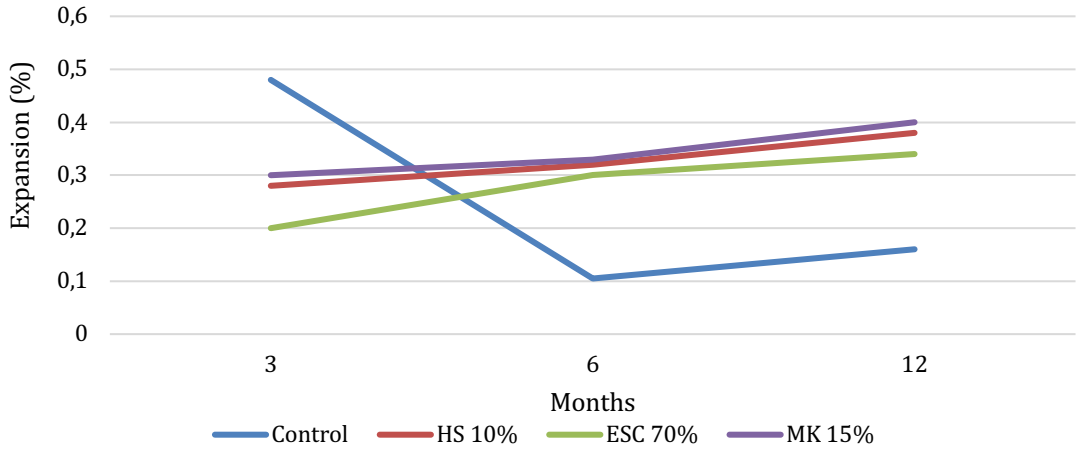


Fig. 5. Expansion (%) due to sulfate attack in mortars with mineral additions under controlled conditions. Data represent ranges from the reviewed studies [26–30]

Under sulfate exposure conditions reported in the reviewed studies, typically involving immersion in sodium sulfate solutions for periods ranging from 6 to 12 months at approximately 20 °C, mixtures containing GGBFS at replacement levels of 50% or higher generally exhibited expansions below 0.05%, corresponding to reductions of approximately 65–70% relative to control mixtures. This enhanced performance is primarily attributed to reduced permeability and changes in pore solution chemistry, which limit the formation of expansive sulfate reaction products. Similarly, silica fume (≈10%) and metakaolin (≈15%) improved sulfate resistance by refining the pore structure and reducing the ingress of sulfate ions. Both SCMs were associated with reductions in sulfate-induced mass loss exceeding 30% under comparable exposure conditions. However, their mechanisms differ slightly: silica fume primarily acts through pore refinement and matrix densification, whereas metakaolin additionally contributes through its high pozzolanic reactivity and reduction of calcium hydroxide availability.

Among the evaluated SCMs, GGBFS generally demonstrated the highest resistance to sulfate attack, particularly under long-term exposure conditions, while silica fume and metakaolin provided moderate to high resistance depending on replacement level and curing conditions. Nevertheless, inter-study variations were observed due to differences in sulfate concentration, exposure duration, SCM content, and testing procedures. At elevated temperatures (>60 °C), all systems showed higher expansion values and localized cracking. Thermal exposure promotes microcrack development and increases pore connectivity, facilitating sulfate ingress. Although slag-rich mixtures maintained better performance than conventional concrete, their resistance may decrease under prolonged thermal cycling above 40 °C owing to the combined effects of thermal damage and chemical attack.

3.3 Microstructural Analysis

SEM and EDS analyses show that mixtures containing silica fume and metakaolin develop denser microstructures with reduced portlandite content. TGA results indicate reductions of up to 40% in $Ca(OH)_2$ [46,47]. A strong negative correlation ($r = -0.85$) is observed between total porosity and compressive strength (see Figure 6) [48-50]. At curing temperatures around 60 °C, increased microcracking and higher pore connectivity are reported [51-52]. Additional techniques (MIP, XRD) indicate the formation of secondary phases in systems containing metakaolin and slag, while nanoindentation results show a more uniform elastic modulus distribution [53]. These observations are complemented by the schematic representation shown in Figure 7, which illustrates the evolution of C–S–H phases under increasing temperature.

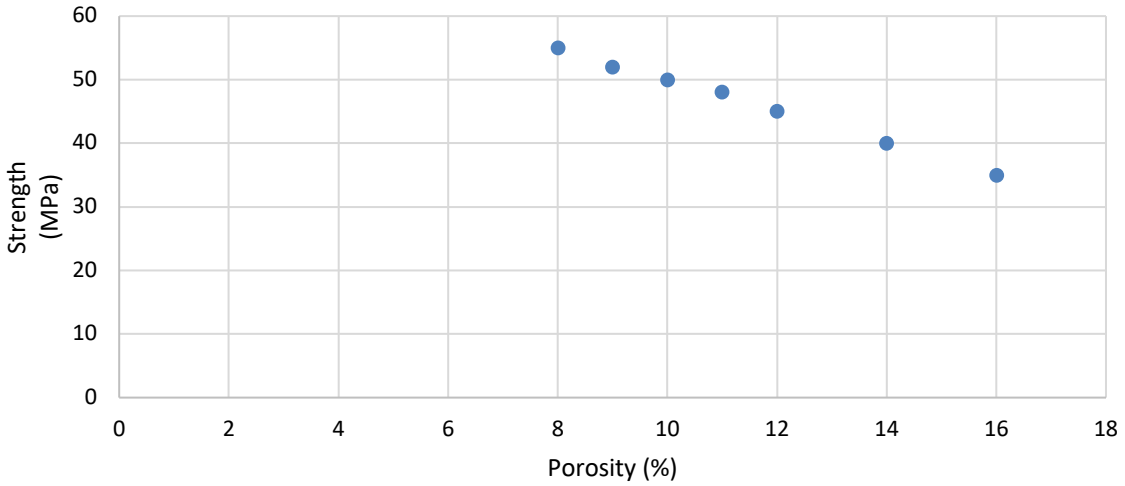


Fig. 6. Relationship between total porosity (%) and compressive strength (MPa) of concrete. Values represent correlations reported in the literature [34,35]

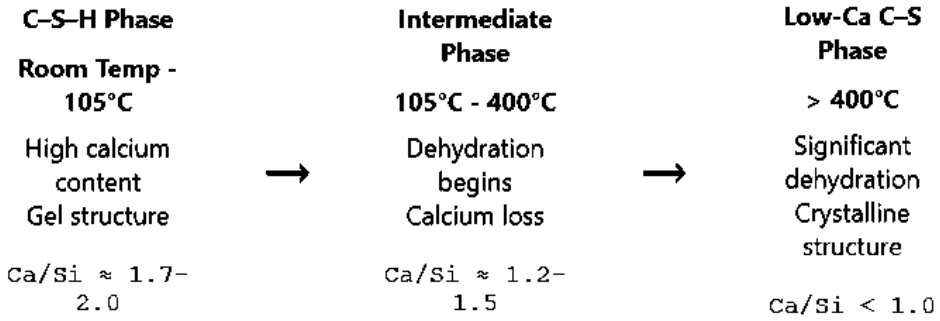


Fig. 7. Schematic representation of C–S–H transformation into low-calcium C–S phases with increasing temperature (°C). Adapted from previous studies [5,15]

3.4 Comparative Statistical Analysis

Multifactorial ANOVA analyses reported in the reviewed literature [54] indicate that SCM type, curing temperature, and testing age significantly influence both mechanical performance and durability indicators ($p < 0.05$). In the referenced studies, the analyzed response variables included compressive strength, chloride migration coefficient, and sulfate resistance, while the main factors considered were SCM type, replacement level, curing temperature, and testing age. The reported statistical outcomes were extracted directly from the original publications and are presented to illustrate the relative influence of thermal and material parameters on concrete performance. Therefore, the statistical results discussed in this review correspond to findings reported by the original authors and do not represent a new statistical analysis performed as part of the present study.

Based on the comparative analysis of the reviewed studies, mixtures incorporating approximately 10% silica fume and 15% metakaolin exhibited the most balanced overall performance in terms of compressive strength, durability indicators, and resistance to chloride and sulfate attack (see Figure 8). This observation is based on the combined evaluation of strength development, durability performance, and microstructural refinement reported in the selected studies. The improved performance is attributed to the synergistic effects of pore structure densification, reduced permeability, and enhanced pozzolanic activity, which collectively contribute to increased long-term durability.

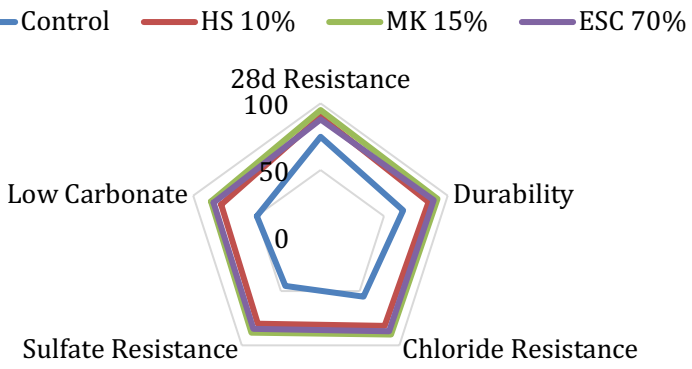


Fig. 8. Comparative performance assessment of concrete mixtures incorporating different supplementary cementitious materials (SCMs)

The evaluation considers five performance indicators: 28-day compressive strength, overall durability, chloride resistance, sulfate resistance, and sustainability-related performance. Scores were derived from a comparative synthesis of the reviewed literature and represent relative performance indices on a normalized scale (0–100), based on trends reported in the selected studies rather than direct experimental measurements from a single dataset. The comparison integrates findings related to mechanical properties, durability behavior, and environmental performance reported in the literature [18,24]. Curing temperature accounts for approximately 35% of the total variance in durability indicators, highlighting its significant influence. Table 2 summarizes the performance of different mineral additions under varying thermal conditions.

Table 2. Synthesized performance ranges of concrete incorporating supplementary cementitious materials under different thermal regimes [55-56]

Type of addition	Temperature range (°C)	Change in compressive strength (%)	Change in chloride migration coefficient (%)	Durability observations
Silica fume (10%)	20–40	+20 – 25	−55 – 60	Excellent performance; dense and compact structure.
Silica fume (10%)	>60	−10 – 15	+25	Formation of thermal microcracks and partial loss of cohesion.
Fly ash (30–35%)	20–40	−10 – 5	−20	Slow early strength development.
Fly ash (30–35%)	40–60	+15 – 25	−40	Enhanced thermal activation; refined pore structure and reduced permeability.
Ground granulated blast-furnace slag (50%)	20–60	+10 – 20	−35 – 45	Good balance of strength and durability across a wide thermal range.
Metakaolin (15%)	20–40	+25 – 30	−50 – 60	High reactivity and densified microstructure.
Metakaolin (15%)	>60	−5 – 10	+15	Reduced reactivity and occurrence of localized cracking.

Note. Values represent synthesized ranges extracted from multiple experimental studies included in the review and do not correspond to a single experimental dataset. The reported percentages indicate the variation relative to the corresponding control mixtures described in the original studies. The values were grouped according to SCM type and temperature range to facilitate comparison of performance trends under different thermal conditions. SCM: supplementary cementitious materials; GGBFS: ground granulated blast-furnace slag.

The data presented in Table 3 show that increasing SCM content leads to estimated CO_2 reductions of up to 60% at high replacement levels (50% SCM) and elevated curing temperatures (50 °C). The results indicate a progressive increase in emission reduction with increasing SCM content, although the reported values represent synthesized estimates derived from the reviewed literature.

Table 3. Relationship between SCM content, curing temperature, and estimated CO_2 reduction [19,22]

Curing Temperature (°C)	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
50	16	20	25	29	34	38	42	47	51	56	60
47	14	18	23	27	32	36	41	45	50	54	59
44	12	17	21	26	30	35	39	43	48	52	57
41	11	15	20	24	29	33	37	42	46	51	55
38	9	14	18	23	27	31	36	40	44	49	53
35	8	12	17	21	25	30	34	38	43	47	51
32	6	11	15	19	24	28	32	37	41	45	50
29	5	9	13	18	22	26	31	35	39	45	48
26	3	7	12	16	20	25	29	33	37	42	46
23	2	6	10	14	19	23	27	31	36	40	44
20	0	4	9	13	17	21	26	30	34	38	43

Supplementary Cementitious Material (SCM) Content (%)

Metric	Value	Details
Maximum CO_2 Reduction	58%	at 50% SCM, 50°C
Minimum CO_2 Reduction	0%	at 0% SCM (Control)
Favorable Thermal Range	40–50%	SCM at ≥35°C
Temperature Effect	+38%	20°C → 50°C at 50% SCM

Note. CO_2 reduction (%) values represent synthesized estimates derived from the reviewed literature and are expressed relative to conventional concrete without SCM replacement. The calculations are based on the reduction of clinker content associated with increasing SCM replacement levels and do not account for potential variations in transportation, processing, or curing energy requirements.

3.5 Field Case Studies under High-Temperature Conditions

Field observations from real structures exposed to high-temperature environments are summarized in Table 4. The field case studies presented in Table 4 provide practical evidence supporting the trends identified in the experimental and numerical studies reviewed throughout this work. Across different climatic regions, prolonged exposure to elevated temperatures was consistently associated with accelerated hydration reactions, increased drying shrinkage, microcracking, higher permeability, and potential reductions in long-term durability. However, the magnitude of these effects varied depending on concrete composition, curing practices, and the incorporation of supplementary cementitious materials (SCMs).

Structures incorporating optimized mixtures, particularly those containing SCMs and low water-to-binder ratios, generally exhibited improved resistance to thermal exposure and reduced deterioration rates. The UHPC bridge deck reported by Yang et al. [58], for example, maintained excellent durability performance under subtropical conditions, whereas conventional concretes exposed to hot and desert climates showed greater susceptibility to cracking and permeability increases. These observations highlight the importance of adapting mixture design, curing procedures, and material selection to the expected service-temperature conditions.

Overall, the combined evidence from laboratory investigations, numerical simulations, and field applications confirms that temperature is a governing parameter influencing the mechanical performance, durability, and long-term service life of concrete. Consequently, an integrated

understanding of temperature-dependent behavior is essential for the development of more durable, sustainable, and climate-resilient concrete structures.

Table 4. Case studies of concrete structures exposed to high-temperature climates [57-60]

Ref.	Location (Climate)	Structure Type	Concrete Type (and Key Features)	Maximum Ambient Temperature (°C)	Exposure Duration	Key Findings
[57]	Bangkok, Thailand (Tropical)	Mass concrete foundation	Ordinary Portland cement concrete (w/c = 0.45); hydration kinetics modelling	Up to 40–45	Short-term tests (up to 28 days) + modelling	Higher temperatures accelerate hydration rate. Early-age strength increases, but long-term durability may be compromised due to higher porosity.
[58]	Shenzhen, China (Subtropical)	Bridge deck (UHPC)	Ultra-high-performance concrete (UHPC); low w/b (0.18) with silica fume	Up to 38–42	Long-term (up to 2 years)	UHPC demonstrates excellent resistance to high temperatures, with minimal strength degradation and a limited increase in permeability.
[59]	Riyadh, Saudi Arabia (Desert)	High-rise building columns	High-performance concrete (HPC); w/c = 0.35 with fly ash	Up to 48–52	3–5 years	Elevated temperatures increase drying shrinkage. Proper curing and supplementary cementitious materials (SCMs) significantly improve long-term durability.
[60]	Phoenix, USA (Hot-dry)	Concrete pavement slabs	Conventional concrete (w/c = 0.50) with calcium aluminate cement	Up to 46–50	5–10 years	High surface temperatures promote microcracking. The use of shrinkage-reducing admixtures and optimized joint design improves pavement performance.

4. Discussion

This systematic review identifies consistent patterns in the behavior of concrete incorporating mineral additions under varying thermal conditions, while also highlighting key uncertainties and existing research gaps.

4.1 Temperature–Mineral Additive Interaction

The reviewed literature consistently demonstrates that curing temperature is one of the most influential parameters governing the performance of supplementary cementitious materials (SCMs). However, the thermal response varies significantly among SCM types. Silica fume and metakaolin exhibit high reactivity and achieve optimal performance under moderate curing temperatures (20–40 °C), where they promote rapid pore refinement and microstructural densification. In contrast, fly ash generally requires moderately elevated temperatures (40–60 °C) to enhance its pozzolanic activity and strength development. GGBFS exhibits a more stable response across a wider temperature range due to its latent hydraulic properties, resulting in a more balanced combination of strength and durability. These differences highlight the importance of selecting SCMs according to the expected thermal conditions during curing and service life [15].

This behavior is associated with accelerated hydration kinetics at temperatures exceeding 60 °C, which promote rapid precipitation of hydration products and early matrix densification. However, this accelerated process leads to a less homogeneous microstructure, broader pore size distribution, and limited long-term refinement, ultimately reducing mechanical performance. This finding contrasts with common practices in precast construction, where elevated curing temperatures are used to accelerate production cycles [59]. Silica fume shows reduced efficiency

above 60 °C due to rapid precipitation of hydration products that limit further pozzolanic reaction. In contrast, Class F fly ash becomes more reactive at moderately elevated temperatures due to improved activation of its vitreous phases, indicating a strong interaction between temperature and reaction kinetics.

4.2 Durability and Deterioration Mechanisms

The results demonstrate that supplementary cementitious materials (SCMs) do not provide uniform resistance across all deterioration mechanisms [60]. Their effectiveness depends not only on SCM type, but also on the interaction between temperature, microstructural evolution, and exposure conditions. Under moderate temperatures (20–40 °C), silica fume and metakaolin significantly improve resistance to chloride ingress by refining the pore structure, reducing pore connectivity, and densifying the interfacial transition zone (ITZ). These changes limit chloride transport and enhance the protective capacity of the cementitious matrix. However, at elevated temperatures, thermally induced microcracking and ITZ degradation increase permeability and create preferential pathways for chloride penetration, partially reducing the durability benefits provided by these SCMs [22,23].

GGBFS generally exhibits superior resistance to sulfate attack due to its ability to reduce permeability, decrease calcium hydroxide availability, and modify pore solution chemistry, thereby limiting the formation of expansive sulfate reaction products. Nevertheless, under significant thermal variations (>40 °C), repeated expansion and contraction can induce microstructural damage and increase pore-network connectivity, facilitating sulfate ingress and accelerating deterioration processes [61].

An important aspect is the interaction between deterioration mechanisms. Thermally induced microcracks formed within the cement matrix and the ITZ increase the connectivity of the pore network, promoting both chloride ingress and sulfate penetration. Increased chloride concentrations may accelerate reinforcement corrosion and contribute to alkalinity reduction, while sulfate attack generates expansive products that induce internal stresses and further crack propagation. Consequently, the combined action of temperature, chloride exposure, and sulfate attack produces greater deterioration than any single mechanism acting independently. These observations highlight the critical role of microstructural integrity and ITZ stability in controlling long-term durability. Therefore, durability assessment should consider coupled thermal, chemical, and transport mechanisms rather than isolated deterioration processes, as actual service environments involve the simultaneous interaction of multiple degradation factors.

4.3 Durability Performance

Durability is strongly influenced by both SCM type and thermal exposure. At moderate temperatures (20–40 °C), mineral additions improve performance by reducing permeability and enhancing resistance to chloride and sulfate attack. However, at temperatures exceeding 60 °C, durability decreases despite early strength gains. This is related to increased pore connectivity, heterogeneous microstructure, and the formation of microcracks, which accelerate the ingress of aggressive agents. Under cyclic thermal conditions, repeated expansion and contraction further intensify damage accumulation. Therefore, durability cannot be considered independently of thermal exposure and must be evaluated as a coupled phenomenon.

4.4 Microstructural Considerations

Microstructural analysis confirms that total porosity alone does not fully explain durability performance [63-65]. The connectivity of the pore network and distribution of hydration products play a fundamental role. Concrete cured at elevated temperatures develops weaker interfacial transition zones and more connected pore networks, even when total porosity remains similar [66]. Additionally, portlandite consumption does not show a direct correlation with durability when thermal variations are considered. These findings indicate that SCM characterization must incorporate thermal effects to accurately predict long-term performance.

4.5 Synthesis of Results and Overall Trends

The combined analysis of the reviewed studies reveals several consistent trends. First, temperature significantly influences hydration kinetics and strength development. Elevated curing temperatures accelerate early reactions but compromise long-term performance. Second, SCM performance depends strongly on thermal sensitivity. Silica fume and metakaolin perform best under moderate temperatures, while fly ash benefits from moderate thermal activation. GGBFS demonstrates more stable behavior across a wider temperature range.

Third, durability properties such as chloride resistance and sulfate resistance are closely linked to microstructural characteristics. High temperatures reduce these benefits by increasing pore connectivity and promoting microcracking. Overall, temperature is shown to be a governing parameter controlling both mechanical and durability performance, and therefore must be treated as a primary design variable.

4.6 Phase Stability and Thermal Transformations

At temperatures above 50–60 °C, the C–S–H gel undergoes partial depolymerization, characterized by reduced silicate chain connectivity and a decrease in the Ca/Si ratio. This leads to the formation of weaker and more permeable phases [15]. Additional transformations, including portlandite decomposition and ettringite conversion, contribute to internal stress development and microcrack initiation.

At moderate temperatures, SCMs such as silica fume and metakaolin enhance microstructural densification. However, these benefits decrease at higher temperatures due to thermal damage. Fly ash shows improved performance at intermediate temperatures but becomes unstable at higher temperatures, while GGBFS maintains more stable behavior across a broader thermal range.

4.7 Applications in High-Temperature Environments

Field observations confirm the trends identified experimentally. In regions where service temperatures frequently exceed 40 °C, concrete structures often experience accelerated moisture loss, increased drying shrinkage, higher permeability, and gradual reductions in long-term durability [67]. Projects incorporating optimized SCM combinations demonstrate improved resistance to thermal cycles and durability degradation [68]. However, the selection of SCM type and dosage should be adapted to the expected thermal exposure conditions. Based on the reviewed literature, silica fume (approximately 8–12%) and metakaolin (10–15%) are recommended for structures exposed to moderate service temperatures (20–40 °C), where their high pozzolanic reactivity promotes microstructural densification and reduced permeability. In contrast, fly ash (25–35%) and GGBFS (40–60%) are generally more suitable for hot climates and mass concrete applications because their slower reaction kinetics help reduce heat generation and enhance long-term durability.

Curing practices are also critical. Prolonged exposure to curing temperatures above 60 °C should be avoided whenever possible, as excessive thermal gradients may induce microcracking and compromise long-term performance. In hot-weather concreting, measures such as temperature-controlled curing, moisture-retention techniques, and staged placement procedures should be implemented to minimize early-age thermal damage. From a design perspective, service-temperature conditions should be considered during mixture proportioning. Structures expected to operate under sustained temperatures above 40 °C may benefit from lower water-to-binder ratios, increased SCM contents, and enhanced durability specifications to compensate for the increased risk of chloride ingress, sulfate attack, and thermally induced deterioration. These findings highlight the importance of temperature-adapted mix design as a practical strategy for improving both durability and sustainability in concrete infrastructure.

4.8 Sustainability and Circular Economy Implications

The use of supplementary cementitious materials (SCMs) significantly reduces CO_2 emissions by decreasing clinker content, which is the main contributor to the carbon footprint of conventional cement production [1]. As shown in Table 3, the estimated CO_2 reduction increases progressively

with SCM replacement level, reaching values of up to 60% at high replacement rates (50% SCM content) under the evaluated conditions. The reported values represent synthesized estimates derived from the reviewed literature and were calculated relative to conventional concrete mixtures without SCM substitution. These estimates are primarily based on reductions in clinker consumption and therefore reflect the potential environmental benefits associated with replacing Portland cement with industrial by-products such as fly ash and GGBFS. For moderate replacement levels, CO_2 reductions typically range between 25% and 45%, while higher replacement levels can result in substantially greater emission savings [1].

However, the analysis has certain limitations. The reported CO_2 reductions do not account for potential variations associated with raw material transportation, processing requirements, regional energy mixes, or additional energy consumption related to elevated-temperature curing. Consequently, the presented values should be interpreted as indicative estimates rather than complete life-cycle assessments. Despite these limitations, the results clearly demonstrate that SCM incorporation can simultaneously improve durability performance and reduce environmental impact. Therefore, the optimal selection of SCM type and replacement level should consider both engineering performance requirements and sustainability objectives. Furthermore, the integration of SCMs into concrete production supports circular economy principles by valorizing industrial by-products and reducing reliance on clinker-intensive cement production, thereby contributing to the decarbonization of the construction sector.

4.9 Limitations and Research Needs

Despite extensive research, several limitations remain. Most studies are conducted under controlled conditions, while real structures are exposed to variable thermal cycles. Field observations further support the trends identified experimentally. Studies conducted on cementitious materials exposed to elevated temperatures have reported noticeable reductions in mechanical strength and increased permeability over time, particularly when temperatures exceed 40 °C [67,69]. In addition, experimental investigations on mortars incorporating recycled polyethylene terephthalate (PET) have demonstrated that high-temperature exposure leads to significant degradation in mechanical resistance, confirming the sensitivity of cement-based composites to thermal conditions [67]. These findings are consistent with laboratory-scale observations reported in this study, reinforcing the reliability of the identified performance trends under real or simulated thermal environments.

Complementary numerical and experimental analyses have also highlighted the impact of temperature on structural performance. Simulation-based studies indicate that thermal exposure alters stress distribution and load-bearing capacity in cementitious materials, contributing to reduced flexural strength under extreme conditions [68]. Furthermore, recent research has shown that external factors such as temperature can intensify damage mechanisms, influencing both material integrity and structural response under loading conditions [70,71]. These results emphasize the importance of integrating thermal effects into durability assessments, particularly in structures subjected to harsh environmental conditions.

Long-term performance data are limited, and current predictive models do not fully integrate thermal, chemical, and microstructural interactions. Future research should focus on developing multi-physics models and integrating advanced characterization techniques such as nano-CT and AI-based prediction tools. Overall, temperature is identified as a governing parameter in the performance of concrete with mineral additions, requiring an integrated approach that combines mechanical, durability, and sustainability considerations.

5. Conclusions

This study demonstrates that curing temperature and service conditions are critical factors influencing both the mechanical performance and long-term durability of concrete incorporating supplementary cementitious materials (SCMs). The results indicate that silica fume (10%) and metakaolin (15%) achieve optimal performance at curing temperatures between 20 °C and 40 °C,

increasing 28-day compressive strength by approximately 22–25% and up to 30%, respectively, compared with control mixtures.

Fly ash mixtures containing approximately 35% replacement exhibit lower early-age strength, showing reductions close to 10% at 7 days; however, they exceed the compressive strength of conventional concrete by approximately 15% after 90 days when curing temperatures range between 40 °C and 60 °C. In contrast, temperatures exceeding 60 °C increase early-age strength by approximately 18–22% but may reduce long-term strength by 10–15% due to the crossover effect and microstructural coarsening. Regarding durability, silica fume and metakaolin reduce the chloride migration coefficient by approximately 55–60%, while GGBFS mixtures containing 50% or more slag reduce sulfate-related expansion by approximately 65–70% relative to control concretes. However, elevated temperatures promote microcracking, pore connectivity, and interfacial transition zone degradation, partially reducing these durability benefits.

The microstructural analysis confirms a strong inverse relationship between porosity and compressive strength ($r = -0.85$), highlighting the importance of pore refinement and matrix densification. Nevertheless, under elevated temperatures, durability becomes increasingly controlled by pore connectivity and thermally induced microcrack propagation rather than total porosity alone. From a sustainability perspective, increasing SCM replacement levels resulted in estimated CO_2 reductions ranging from approximately 25–45% for moderate replacement rates and up to 60% for high SCM contents under the evaluated conditions. These findings demonstrate that SCM incorporation can simultaneously enhance durability and reduce the environmental impact of concrete production. Overall, the results indicate that silica fume and metakaolin are most suitable for moderate-temperature applications (20–40 °C), fly ash performs more effectively under moderately elevated temperatures (40–60 °C), and GGBFS provides the most stable durability performance across a wide thermal range. Consequently, SCM selection and dosage should be adapted to expected thermal exposure conditions in order to optimize both structural performance and sustainability.

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