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Review Article

Durability Performance of Supplementary Cementitious Materials in Aggressive Environments: A Critical Review

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Abstract

Concrete durability is a critical factor influencing the longevity, safety, and sustainability of infrastructure, particularly under aggressive environmental conditions. Conventional ordinary Portland cement (OPC) concrete is susceptible to deterioration mechanisms such as chloride-induced reinforcement corrosion, sulphate attack, carbonation, and acid degradation, which compromise structural integrity and service life. The partial replacement of OPC with supplementary cementitious materials (SCMs) has emerged as an effective strategy to enhance durability while reducing the environmental footprint of concrete. This review critically examines the performance of major SCMs, including fly ash, ground granulated blast furnace slag (GGBS), silica fume, metakaolin, rice husk ash (RHA), and limestone calcined clay cement (LC3), in aggressive environments. The review highlights how SCMs influence microstructural properties, such as pore refinement, chloride binding, and formation of secondary hydration products, thereby improving resistance to chloride ingress, sulphate attack, carbonation, and acid exposure. While SCMs generally enhance durability, certain limitations, such as increased carbonation depth in high-volume fly ash and slag systems, are discussed. Furthermore, factors influencing performance such as SCM type, replacement level, curing conditions, and exposure environment are analysed.

Keywords: Concrete durability, Supplementary cementitious materials, Fly ash, GGBS, LC3, Aggressive environments, Chloride ingress, Sulphate attack, Carbonation, Acid resistance.

INTRODUCTION

Concrete is the most widely used construction material worldwide due to its versatility, availability of raw materials, and cost effectiveness. However, the long-term performance of concrete structures is predominantly governed by durability rather than strength alone. In aggressive exposure conditions such as chloride-laden marine environments, sulphate-rich soils, industrial acidic atmospheres, and carbonation-prone urban settings, conventional ordinary Portland cement (OPC) concrete often experiences premature deterioration. This deterioration manifests in the form of reinforcement corrosion, loss of mechanical integrity, cracking, spalling, and reduced service life, leading to substantial economic losses and increased environmental burden due to repair and rehabilitation activities (Mehta and Monteiro, 2014; Neville, 2011).

Durability-related failures of reinforced concrete structures have raised significant concerns among researchers and practitioners, particularly in the context of sustainable infrastructure development. Chloride-induced corrosion is recognized as one of the most critical durability problems affecting reinforced concrete structures exposed to marine environments and de-icing salts. Similarly, sulphate attack can cause expansion, cracking, and softening of cementitious matrices, while carbonation lowers the alkalinity of concrete, increasing the susceptibility of embedded steel to corrosion. Acid attack, though less common, can be severe in industrial and wastewater environments, resulting in rapid degradation of cement paste (Thomas, 2013; Shi *et al.,*2015).

In parallel with durability challenges, the cement industry is under increasing pressure to reduce its environmental footprint. The production of OPC is responsible for approximately 7–8% of global anthropogenic CO_2 emissions, primarily due to limestone calcination and high energy consumption during clinker production. Consequently, the partial replacement of OPC with supplementary cementitious materials (SCMs) has emerged as a key strategy to

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enhance both the durability and sustainability of concrete (Scrivener *et al.,*2018). SCMs are generally industrial by-products or processed natural materials that exhibit pozzolanic or latent hydraulic properties and contribute to improved microstructural and durability performance when incorporated into cementitious systems.

Commonly used SCMs include fly ash, ground granulated blast furnace slag (GGBS), silica fume, metakaolin, rice husk ash, and more recently, limestone calcined clay cement (LC3). These materials influence the hydration process by consuming calcium hydroxide, forming additional calcium silicate hydrate (C–S–H) gel, and refining the pore structure of concrete. As a result, SCM-based concretes typically exhibit reduced permeability and enhanced resistance to the ingress of aggressive ions such as chlorides and sulphates (Taylor, 1997; Thomas, 2013).

A substantial body of experimental research has demonstrated that the incorporation of SCMs significantly improves resistance to chloride penetration, which is directly linked to delayed corrosion initiation of reinforcement. Slag- and silica fume–based concretes, in particular, show markedly lower chloride diffusion coefficients compared to OPC concrete, owing to their dense microstructure and enhanced chloride binding capacity (Thomas and Bamforth, 1999; Shi *et al.,* 2012). Similarly, Class F fly ash has been widely reported to enhance sulphate resistance by reducing the availability of reactive aluminates and lowering permeability, thereby mitigating expansive reactions in sulphate-rich environments (Neville, 2011).

Despite the well-established benefits of SCMs, durability performance is not universally positive under all aggressive conditions. For instance, several studies have reported increased carbonation depth in blended cement systems, especially at high replacement levels of fly ash and slag, due to reduced portlandite content and lower buffering capacity against CO_2 ingress (Papadakis, 2000; Shi *et al.,*2015). This highlights the need for a balanced understanding of the trade-offs associated with SCM incorporation, particularly in structures where carbonation-induced corrosion is a dominant concern.

Furthermore, the durability performance of SCM-based concrete is highly dependent on multiple interacting factors, including SCM type, chemical composition, fineness, replacement level, curing regime, water-to-binder ratio, and exposure conditions. The variability in raw material characteristics and test methodologies across studies often leads to inconsistent conclusions, making it difficult to establish generalized durability trends. In addition, while laboratory-based accelerated tests provide valuable insights, their correlation with long-term field performance remains a subject of ongoing debate (Alexander and Thomas, 2015).

Recent advancements in microstructural characterization techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), thermogravimetric analysis (TGA), and mercury intrusion porosimetry (MIP) have significantly improved the understanding of durability mechanisms in SCM-based concretes. These studies reveal that SCMs contribute to pore refinement, reduced connectivity of capillary pores, and enhanced formation of secondary hydration products, which collectively improve resistance to aggressive agents. Moreover, certain SCMs, such as LC3 systems, exhibit synergistic effects through combined pozzolanic and filler mechanisms, offering promising durability performance even at high clinker replacement levels (Scrivener *et al.,*2018).

Although numerous review articles exist on individual SCMs or specific durability aspects, a comprehensive and critical synthesis focusing on the durability performance of a wide range of SCMs under diverse aggressive environments is still limited. Most existing reviews either emphasize sustainability aspects or focus on a single deterioration mechanism, such as chloride ingress or sulphate attack, without providing a holistic comparison across exposure conditions. Such an integrated perspective is essential for informed material selection and performance-based durability design in modern concrete structures.

Therefore, this paper presents a critical review of the durability performance of concrete incorporating various supplementary cementitious materials when exposed to aggressive environments, including chlorides, sulphates, carbonation, acidic media, and marine conditions. The review systematically examines experimental findings reported in the literature, elucidates the underlying microstructural and chemical mechanisms governing durability, and discusses the implications for service life and sustainability. Finally, key research gaps and future research directions are identified to support the development of durable, low-carbon cementitious materials suitable for long-term infrastructure applications.

Clear Objectives of the Review

This review aims to:

1. Summarize the influence of major supplementary cementitious materials (SCMs) on concrete durability.
2. Evaluate concrete performance under aggressive environments such as chlorides, sulphates, carbonation, acids, and marine exposure.
3. Correlate durability performance with microstructural modifications induced by SCMs.

3. Supplementary Cementitious Materials: Types and Characteristics

Supplementary cementitious materials (SCMs) are finely divided materials that are incorporated into concrete as partial replacements for ordinary Portland cement (OPC) to improve durability, mechanical performance, and sustainability. SCMs contribute to hydration either through pozzolanic reactions, latent hydraulic behavior, or filler effects, leading to refined pore structure and enhanced resistance to aggressive environments. The most commonly used SCMs in durable concrete applications include fly ash, ground granulated blast furnace slag (GGBS), silica fume, metakaolin, rice husk ash, and limestone calcined clay cement (LC3).

3.1 Fly Ash

Fly ash is a by-product of coal combustion in thermal power plants and is one of the most widely used SCMs in concrete. It is generally classified into Class F (low calcium) and Class C (high calcium) fly ash based on its chemical composition. Class F fly ash exhibits strong pozzolanic behavior, reacting with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C–S–H), while Class C fly ash shows both pozzolanic and self-cementing characteristics (Mehta and Monteiro, 2014).

The incorporation of fly ash significantly improves concrete durability by reducing permeability and refining pore structure. Numerous studies have reported enhanced resistance to chloride ingress and sulphate attack in fly ash concrete, particularly at moderate to high replacement levels (20–40%) (Thomas, 2013). However, fly ash blended concretes may exhibit increased carbonation depth due to reduced portlandite content, especially under poor curing conditions. Therefore, the durability performance of fly ash concrete is strongly influenced by curing regime, replacement level, and exposure environment (Papadakis, 2000).

SEM image reveal that fly ash particles are generally spherical and help fill capillary pores in the paste matrix, contributing to pore refinement and reduced permeability. Such densification enhances resistance to chloride ingress and other aggressive agents (Figure 1).

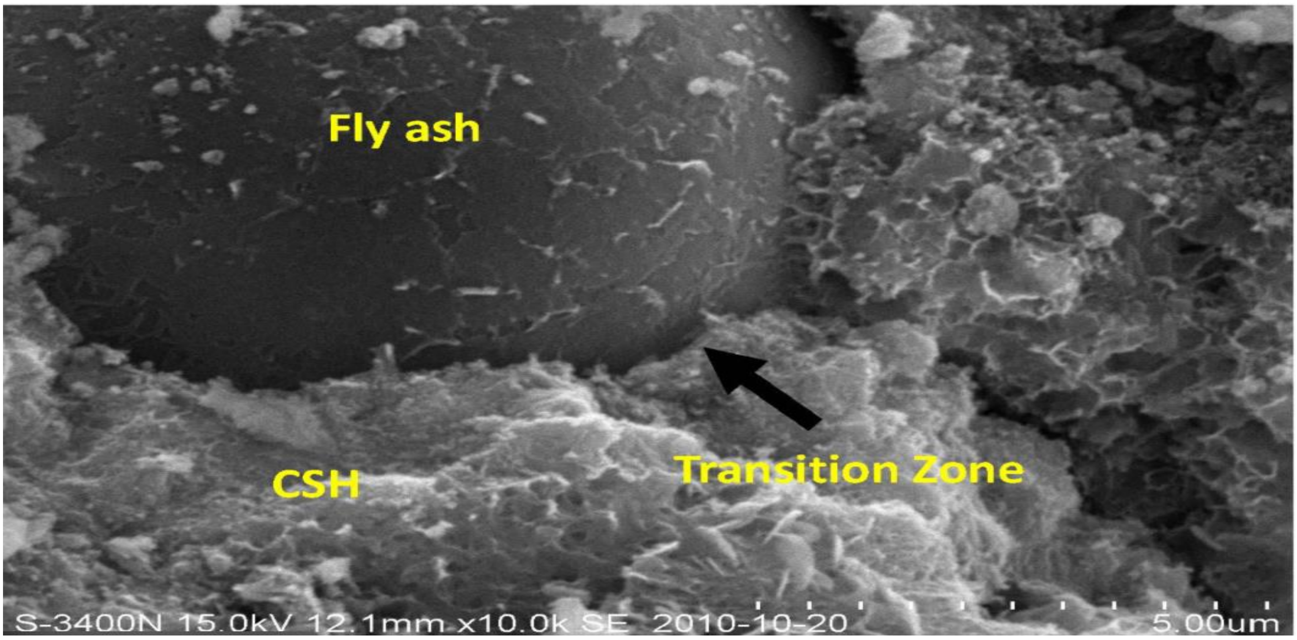
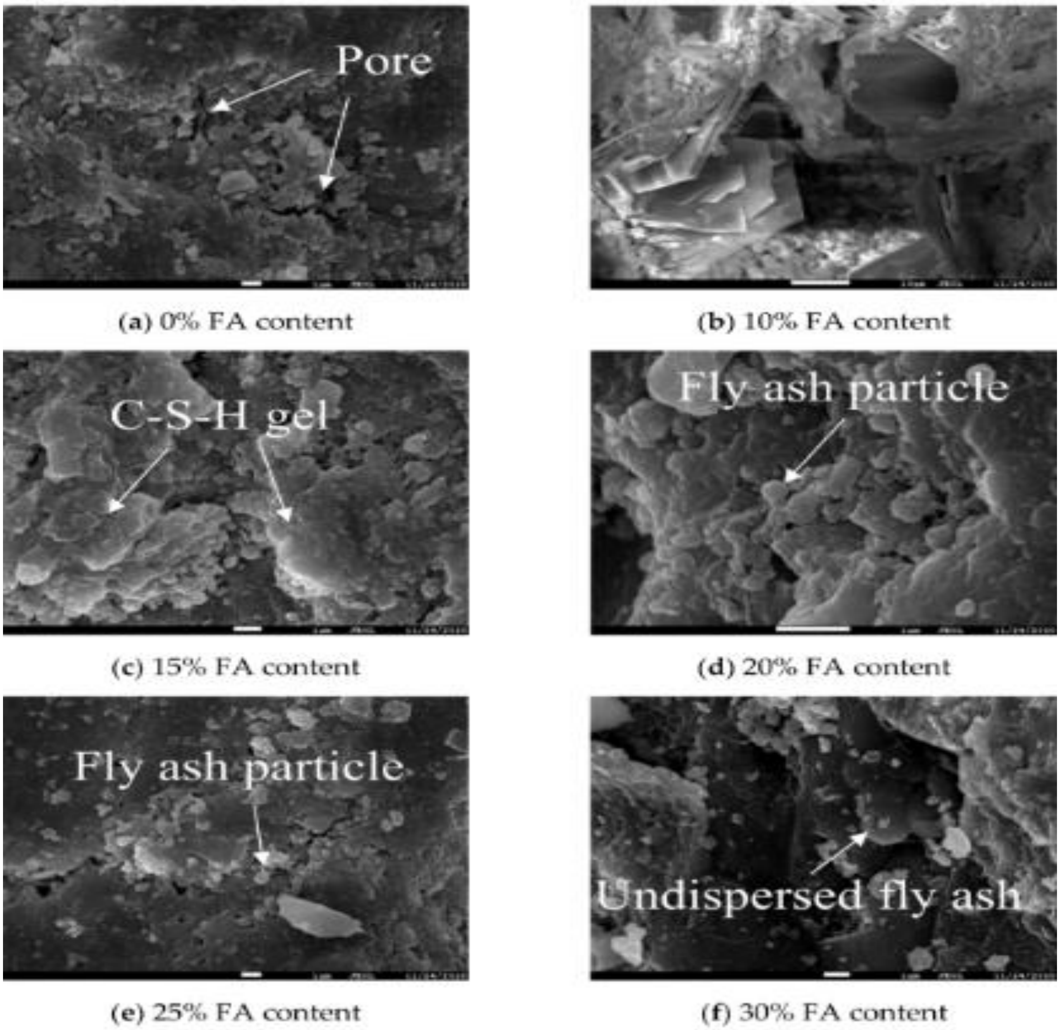


Figure 1: SEM micrograph showing Fly Ash particles embedded in a concrete matrix with C–S–H gel, illustrating how fly ash fills pores and contributes to densification



(a) 0% FA content

(b) 10% FA content

(c) 15% FA content

(d) 20% FA content

(e) 25% FA content

(f) 30% FA content

Figure 2: SEM images of concrete microstructure with various fly ash contents showing reduced pores and enhanced C–S–H gel formation as fly ash increases (0%, 15%, 20%, etc.)

3.2 Ground Granulated Blast Furnace Slag (GGBS)

GGBS is a latent hydraulic material produced by rapid quenching of molten blast furnace slag, followed by grinding to a fine powder. When activated by the alkaline environment of cement hydration, GGBS reacts to form C–S–H with a lower calcium-to-silica ratio compared to OPC systems. This leads to a denser and more refined microstructure (Taylor, 1997).

Concrete containing GGBS is well known for its superior resistance to chloride penetration, making it particularly suitable for marine and coastal structures. Several researchers have reported significantly lower chloride diffusion coefficients and enhanced chloride binding capacity in slag-based concretes compared to OPC concrete (Thomas and Bamforth, 1999; De Weerdt *et al.,*2014). In addition, GGBS improves sulphate resistance and reduces the risk of alkali–silica reaction. However, similar to fly ash, increased carbonation susceptibility has been reported in high-slag systems, necessitating careful consideration in carbonation-prone environments (Shi *et al.,*2015).

3.3 Silica Fume

Silica fume is an ultra-fine, amorphous silicon dioxide by-product obtained during the production of silicon and ferrosilicon alloys. Due to its extremely high fineness and high pozzolanic reactivity, silica fume significantly enhances the microstructural densification of cementitious matrices through both pozzolanic and filler effects (Aïtcin and Mindess, 2011).

The incorporation of silica fume at low replacement levels (5–10%) results in substantial reductions in permeability and water absorption. Consequently, silica fume concrete exhibits excellent resistance to chloride ingress and improved corrosion protection of reinforcement. However, silica fume increases water demand and may lead to higher autogenous shrinkage if not properly managed. Additionally, its influence on carbonation resistance is generally favorable due to pore refinement, although this depends on mixture design and curing quality (Bentz, 2010).

3.4 Metakaolin

Metakaolin is a highly reactive pozzolan produced by the controlled calcination of kaolinitic clay at temperatures between 650 and 800 °C. Unlike industrial by-products, metakaolin is a purpose-made SCM with consistent chemical and mineralogical composition, resulting in predictable performance in concrete (Juenger *et al.,*2011).

Metakaolin contributes to enhanced early-age strength and improved durability by accelerating hydration and refining pore structure. Studies have demonstrated improved resistance to chloride penetration, sulphate attack, and acid exposure in metakaolin-modified concretes. Furthermore, metakaolin reduces the alumina content available for deleterious expansive reactions, thereby enhancing chemical resistance. However, its higher cost compared to other SCMs may limit widespread application in large-volume concrete works (Neville, 2011).

3.5 Rice Husk Ash

Rice husk ash (RHA) is an agricultural by-product obtained from the controlled burning of rice husks. When produced under appropriate combustion conditions, RHA contains a high proportion of amorphous silica and exhibits strong pozzolanic activity. The use of RHA as an SCM not only improves concrete durability but also contributes to waste utilization and sustainable construction (Mehta, 1992).

Concrete incorporating RHA shows reduced permeability, improved resistance to chloride ingress, and enhanced performance under sulphate and acidic environments. The effectiveness of RHA, however, is highly dependent on its particle size, silica content, and combustion process. Poorly processed RHA may contain crystalline silica or high carbon content, adversely affecting concrete performance. Therefore, quality control remains a critical factor in the successful application of RHA in durable concrete (Ganesan *et al.,*2008).

3.6 Limestone Calcined Clay Cement (LC3)

Limestone calcined clay cement (LC3) is a relatively recent low-carbon cementitious system comprising a combination of calcined clay, limestone, and clinker. LC3 systems typically achieve clinker replacement levels of up to 50% while maintaining comparable mechanical and durability performance to OPC-based concretes (Scrivener *et al.,*2018).

The synergistic interaction between calcined clay and limestone leads to enhanced pozzolanic reactivity and the formation of additional carboaluminate phases, contributing to pore refinement and improved chloride resistance. Recent studies have reported excellent resistance of LC3 concretes to chloride ingress and sulphate attack, making them promising candidates for durable infrastructure in aggressive environments. Moreover, LC3 offers significant reductions in CO_2 emissions, positioning it as a key material for sustainable and durable construction (Scrivener *et al.,*2019).

4. Aggressive Environments Affecting Concrete

Concrete structures are frequently exposed to aggressive environmental conditions that adversely affect their durability and service life. These environments promote physical and chemical deterioration mechanisms that compromise the integrity of the cementitious matrix and accelerate reinforcement corrosion. The severity and nature of deterioration depend on exposure conditions, material composition, and transport properties of concrete. The most critical aggressive environments relevant to reinforced concrete infrastructure include chloride exposure, sulphate attack, carbonation, acid attack, and marine exposure.

4.1 Chloride Exposure

Chloride-induced deterioration is one of the most severe and widespread durability problems affecting reinforced concrete structures. Chloride ions penetrate concrete primarily through diffusion, capillary suction, and permeation, eventually reaching the reinforcement surface and disrupting the passive oxide film that protects steel in the highly alkaline concrete environment. Once depassivation occurs, localized corrosion initiates, leading to cracking, spalling, and loss of structural capacity (Thomas, 2013).

Common sources of chloride exposure include marine environments, de-icing salts used on roadways, and industrial effluents. The rate of chloride ingress is governed by concrete permeability, pore connectivity, and chloride binding capacity. Blended cement systems incorporating supplementary cementitious materials have been shown to significantly reduce chloride diffusion by refining pore structure and enhancing chloride binding through chemical interactions with hydration products. However, the effectiveness of chloride resistance depends strongly on SCM type, replacement level, curing conditions, and exposure duration (De Weerdt *et al.,*2014; Papadakis, 2000).

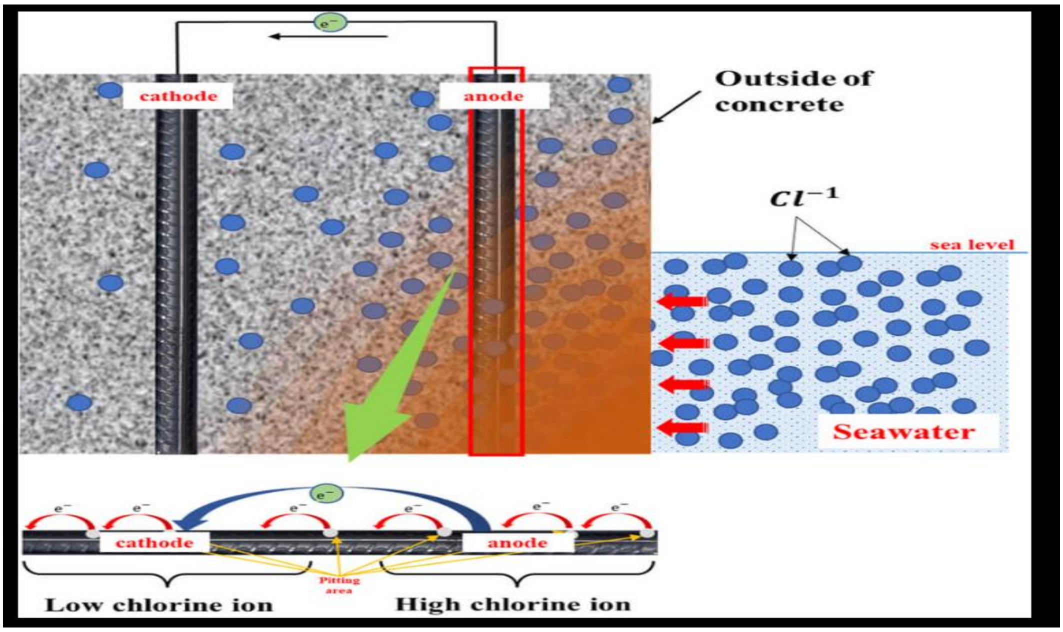


Figure 3: Schematic of a corrosion cell at steel reinforcement caused by chloride exposure in concrete. Adapted from Song and Saraswathy (2007)

4.2 Sulphate Attack

Sulphate attack occurs when sulphate ions present in soil, groundwater, or industrial effluents react with cement hydration products, particularly calcium hydroxide and aluminates, leading to the formation of expansive compounds such as ettringite and gypsum. These reactions cause volumetric expansion, cracking, loss of cohesion, and softening of the cement matrix (Neville, 2011).

Sulphate exposure can be classified as external or internal, with external sulphate attack being more common in foundations and sewage-related structures. The severity of sulphate attack depends on sulphate concentration, cation type, permeability of concrete, and cement composition. SCMs such as Class F fly ash and GGBS are widely reported to improve sulphate resistance by reducing the availability of reactive aluminates and lowering permeability. Nevertheless, excessive sulphate concentrations and poor curing conditions can still result in deterioration even in SCM-modified concretes, highlighting the need for performance-based material selection (Thomas, 2013).

4.3 Carbonation

Carbonation is a physicochemical process involving the diffusion of atmospheric carbon dioxide into concrete, where it reacts with calcium hydroxide and other alkaline hydration products to form calcium carbonate. This reaction reduces the pH of the pore solution from values above 12.5 to below the threshold required to maintain steel passivation, thereby increasing the risk of corrosion (Papadakis, 2000).

Carbonation depth is influenced by factors such as concrete permeability, moisture content, environmental CO_2 concentration, and binder composition. While SCMs generally improve resistance to chloride ingress, blended cement concretes often exhibit increased carbonation depth due to reduced portlandite content and lower alkalinity. This effect is particularly pronounced in concretes with high replacement levels of fly ash or slag under inadequate curing conditions. Consequently, carbonation-induced corrosion remains a critical consideration in the durability design of SCM-based concretes exposed to urban and industrial environments (Shi *et al.,*2015).

4.4 Acid Attack

Acid attack involves the chemical degradation of concrete due to exposure to acidic solutions originating from industrial effluents, sewage systems, agricultural environments, or biogenic processes. Unlike chloride or carbonation-related deterioration, acid attack directly dissolves cement hydration products, particularly calcium hydroxide and C–S–H, leading to progressive mass loss and surface erosion (Mehta and Monteiro, 2014).

The resistance of concrete to acid attack is largely dependent on its permeability and chemical composition. SCMs such as GGBS, metakaolin, and rice husk ash enhance acid resistance by reducing calcium hydroxide content and producing denser microstructures. However, no cementitious system is entirely resistant to strong acids, and the effectiveness of SCMs is limited under highly aggressive acidic conditions. Therefore, material selection for acid-exposed structures often requires a combination of low-permeability concrete, protective coatings, and appropriate design measures (Aïtcin and Mindess, 2011). Concrete exposed to acidic environments exhibits surface erosion and mass loss as the cement paste hydration products are dissolved (Figure 4)

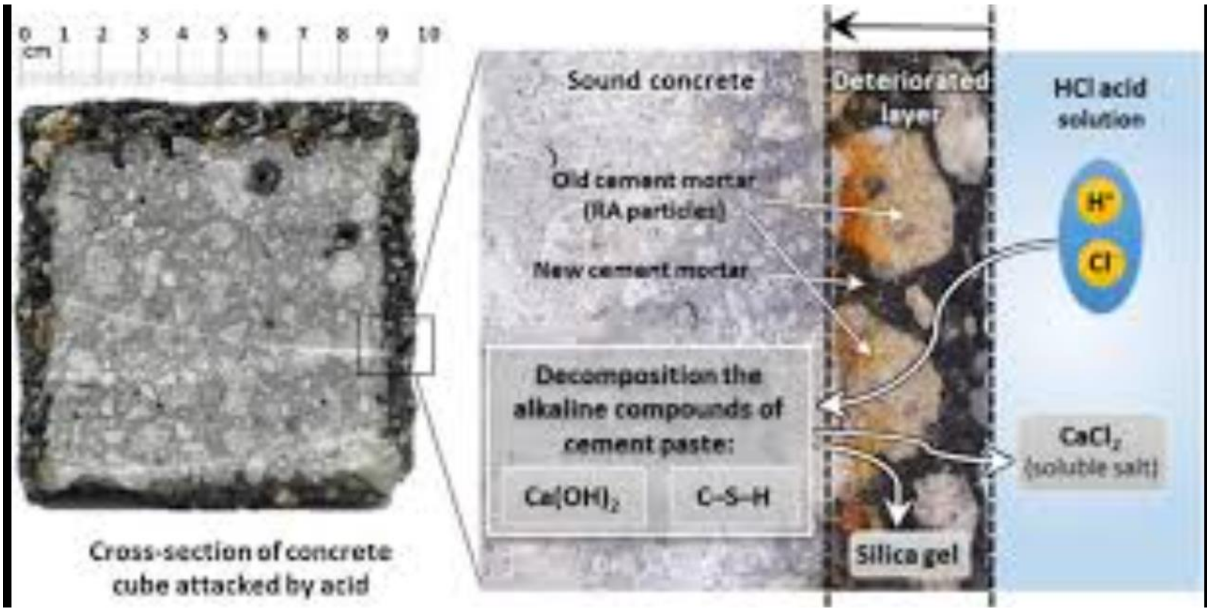


Figure 4: Degraded surface layer of concrete exposed to acidic environment showing loss of cement paste and formation of a porous degraded layer due to dissolution of hydration products (adapted from Gutberlet and Hilbig, 2015)

4.5 Marine Environment

Marine environments represent one of the most complex and aggressive exposure conditions for reinforced concrete structures, combining multiple deterioration mechanisms, including chloride ingress, sulphate attack, wet–dry cycles, temperature variations, and biological activity. Structures such as bridges, offshore platforms, and coastal defenses are particularly vulnerable to accelerated deterioration under marine exposure (Alexander and Thomas, 2015).

The tidal and splash zones are considered the most severe exposure regions due to frequent wetting and drying, which enhances chloride ingress and oxygen availability, thereby accelerating corrosion processes. The use of SCMs in marine concrete has been shown to significantly improve durability by reducing permeability and enhancing resistance to chloride penetration. Slag-based and LC3 concretes, in particular, demonstrate promising performance in marine environments. Nevertheless, long-term field studies are still required to validate laboratory findings and establish reliable service life prediction models for marine-exposed SCM concretes (Scrivener *et al.,*2019).

5. Durability Performance of SCM-Based Concrete

5.1 Resistance to Chloride Ingress

Resistance to chloride ingress is one of the most important durability requirements for reinforced concrete structures exposed to marine environments and de-icing salts. Chloride-induced corrosion is initiated when the chloride concentration at the steel–concrete interface exceeds a critical threshold, leading to breakdown of the passive oxide layer and onset of electrochemical corrosion. The rate of chloride ingress is primarily governed by the transport properties of concrete, including pore size distribution, pore connectivity, and chloride binding capacity (Thomas, 2013).

The incorporation of supplementary cementitious materials has been widely reported to enhance chloride resistance through a combination of physical and chemical mechanisms. Physically, SCMs contribute to pore refinement by generating additional hydration products that reduce capillary porosity and hinder ion transport. Chemically, certain SCMs enhance chloride binding by forming stable chloroaluminate phases, thereby reducing the concentration of free chlorides available for corrosion initiation (Shi and De Schutter, 2004).

Fly ash–based concretes

exhibit significantly reduced chloride diffusion coefficients compared to OPC concrete, particularly at replacement levels between 20% and 40%. Class F fly ash is especially effective due to its low calcium content, which promotes the formation of dense secondary C–S–H gel. Numerous long-term studies have demonstrated that fly ash concrete shows slower chloride penetration under both laboratory and field exposure conditions. However, early-age chloride resistance may be inferior to OPC concrete due to delayed pozzolanic reactions, highlighting the importance of adequate curing and long-term performance assessment (Papadakis, 2000; Thomas, 2013).

Ground granulated blast furnace slag (GGBS)

is widely regarded as one of the most effective SCMs for improving chloride resistance. Slag-based concretes consistently exhibit lower chloride diffusion coefficients than fly ash and OPC concretes, particularly at replacement levels exceeding 40%. This enhanced performance is attributed to a refined pore structure and increased chloride binding capacity resulting from the higher alumina content of slag hydration products. Several studies report reductions in chloride diffusion coefficients by more than 50% in slag concrete compared to OPC systems, making GGBS highly suitable for marine and coastal infrastructure (Thomas and Bamforth, 1999; De Weerdt *et al.,*2014).

Silica fume,

due to its extremely fine particle size and high pozzolanic reactivity, provides exceptional resistance to chloride ingress even at low replacement levels (5–10%). The combined filler and pozzolanic effects lead to a highly dense interfacial transition zone and reduced permeability. Silica fume concrete exhibits very low water absorption and rapid chloride permeability values, making it particularly effective in high-performance concrete applications. Nevertheless, its high cost and potential for increased shrinkage necessitate careful mixture proportioning (Aïtcin and Mindess, 2011).

Metakaolin-modified concretes also demonstrate improved chloride resistance owing to accelerated hydration and pore refinement. Studies indicate that metakaolin enhances early-age chloride resistance more effectively than fly ash, making it advantageous in structures requiring rapid strength development. Additionally, metakaolin contributes to enhanced chloride binding through the formation of alumina-rich hydration products. However, its effectiveness is influenced by dosage and curing quality, and excessive replacement may adversely affect workability (Juenger *et al.,*2011).

Rice husk ash (RHA) has been shown to improve chloride resistance when produced under controlled combustion conditions resulting in high amorphous silica content. RHA contributes to pore refinement and reduced permeability, leading to lower chloride diffusion coefficients. However, variability in RHA quality remains a major challenge, and inconsistent processing can lead to performance variability. Consequently, strict quality control is essential for reliable durability performance of RHA-based concrete (Ganesan *et al.,*2008).

Limestone calcined clay cement (LC3) has emerged as a promising low-carbon binder with excellent resistance to chloride ingress. The synergistic interaction between calcined clay and limestone promotes the formation of additional carboaluminate phases and refined pore structure, significantly reducing chloride transport. Recent studies report that LC3 concretes exhibit chloride resistance comparable to or better than traditional fly ash and slag systems, even at high clinker replacement levels. These findings highlight the potential of LC3 for durable and sustainable construction in aggressive chloride environments (Scrivener *et al.,*2019).

Despite the overall improvement in chloride resistance offered by SCMs, the durability performance of SCM-based concretes is influenced by multiple factors, including curing regime, water-to-binder ratio, exposure conditions, and test methodology. Accelerated laboratory tests, such as rapid chloride permeability tests, may not fully capture long-term field performance. Therefore, a performance-based durability approach incorporating long-term exposure data and service life modeling is essential for reliable application of SCM-based concrete in chloride-rich environments (Alexander and Thomas, 2015).

5.2 Sulphate Resistance

Sulphate resistance is a critical durability requirement for concrete structures exposed to sulphate-bearing soils, groundwater, sewage systems, and industrial effluents. Sulphate attack involves the ingress of sulphate ions (SO_4^{2-}) into concrete and their reaction with cement hydration products, particularly calcium hydroxide and aluminate phases, leading to the formation of expansive compounds such as ettringite and gypsum. These reactions result in volumetric expansion, cracking, loss of strength, and eventual disintegration of the cementitious matrix (Neville, 2011).

The incorporation of supplementary cementitious materials has been widely recognized as an effective strategy to enhance sulphate resistance. Class F fly ash significantly improves resistance to sulphate attack by reducing the content of tricalcium aluminate (C_3A) and calcium hydroxide, thereby limiting the formation of expansive reaction products. Numerous studies reports improved dimensional stability and reduced strength loss in fly ash concrete exposed to sulphate environments, particularly at replacement levels between 25% and 40% (Thomas, 2013).

Ground granulated blast furnace slag (GGBS) exhibits excellent sulphate resistance due to its latent hydraulic nature and ability to produce hydration products with lower calcium content and refined pore structure. Slag-based concretes demonstrate reduced permeability and lower availability of reactive aluminates, making them highly suitable for sulphate-rich environments. However, the resistance of slag concrete may vary depending on sulphate concentration, curing conditions, and slag chemistry (Neville, 2004).

Silica fume and metakaolin contribute to sulphate resistance primarily through pore refinement and reduced permeability. While these SCMs are effective at limiting sulphate ingress, their high alumina content may increase susceptibility to sulphate attack if used in high dosages without adequate mixture optimization. Rice husk ash, when properly processed, also enhances sulphate resistance by reducing permeability and calcium hydroxide content.

Recent studies indicate that LC3 systems exhibit promising sulphate resistance due to the synergistic interaction between calcined clay and limestone, which promotes stable carboaluminate formation and limits deleterious expansive reactions. Nevertheless, long-term field exposure data for LC3 concretes under severe sulphate conditions remain limited, necessitating further investigation (Scrivener *et al.,*2019).

5.3 Carbonation Resistance

Carbonation-induced deterioration is a major concern for reinforced concrete structures exposed to urban and industrial environments. Carbonation occurs when atmospheric carbon dioxide diffuses into concrete and reacts with calcium hydroxide and other alkaline hydration products, forming calcium carbonate and reducing pore solution pH. When the pH drops below approximately 9.5, the passive layer protecting reinforcing steel is destroyed, making the steel susceptible to corrosion (Papadakis, 2000).

SCM incorporation has a complex influence on carbonation resistance. While SCMs generally improve resistance to chloride ingress by refining pore structure, many blended cement systems exhibit increased carbonation depth compared to OPC concrete. This is primarily attributed to the reduced calcium hydroxide content and lower alkalinity of SCM-based concretes, which decrease the buffering capacity against CO_2 ingress (Shi *et al.,*2015). Carbonation occurs when carbon dioxide diffuses into the concrete and reacts with calcium hydroxide and other alkaline hydration products to form calcium carbonate, significantly lowering the pore solution pH and compromising the passive layer on steel reinforcement (Papadakis, 2000).

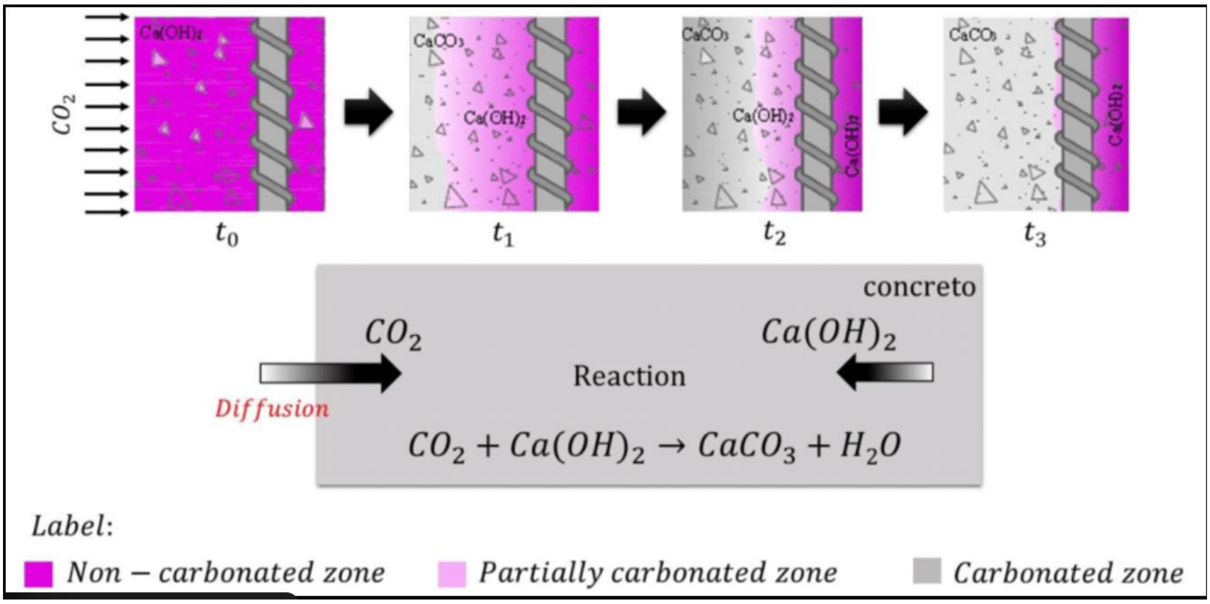


Figure 5: Schematic of the carbonation process in concrete showing CO_2 diffusion into concrete pores, reaction with $Ca(OH)_2$ to form $CaCO_3$, and progression of the carbonation front (adapted from Al-Neshawy *et al.,*2012)

Fly ash and GGBS concretes, particularly at high replacement levels, often show increased carbonation rates under accelerated testing conditions. However, this effect is strongly dependent on curing quality, water-to-binder ratio, and environmental humidity. Adequate curing has been shown to significantly mitigate carbonation susceptibility in SCM-based systems by enhancing hydration and densifying the microstructure.

In contrast, silica fume and metakaolin generally improve carbonation resistance due to their pronounced pore refinement and reduced permeability, provided that mixture design and curing are properly controlled. Rice husk ash exhibits variable carbonation performance depending on ash quality and fineness.

Emerging evidence suggests that LC3 concretes can achieve carbonation resistance comparable to OPC systems despite reduced clinker content. The formation of stable carboaluminate phases and refined pore structure in LC3 systems contributes to improved resistance against CO_2 ingress. However, carbonation behavior of LC3 under natural exposure conditions is still an active research area requiring further long-term validation (Scrivener *et al.,*2018).

5.4 Acid Resistance

Acid resistance is a crucial durability consideration for concrete structures exposed to industrial effluents, sewage systems, agricultural environments, and biogenic acids. Acid attack differs fundamentally from other deterioration mechanisms, as it involves the direct dissolution of cement hydration products, particularly calcium hydroxide and calcium silicate hydrate (C–S–H), leading to progressive surface erosion, mass loss, and loss of structural integrity (Zivica and Bajza, 2001).

Concrete inherently possesses limited resistance to acidic environments due to its alkaline nature. However, the incorporation of SCMs can significantly enhance acid resistance by reducing calcium hydroxide content and producing denser microstructures. GGBS-based concretes have consistently demonstrated superior resistance to acid attack compared to OPC concrete, attributed to their lower calcium content and formation of less soluble hydration products.

Metakaolin and silica fume also improve acid resistance by refining pore structure and reducing permeability, thereby slowing acid ingress. Rice husk ash, when highly amorphous and finely ground, has been shown to improve resistance to mild and moderate acidic environments. Nevertheless, no cementitious system is fully resistant to strong inorganic acids, and SCM effectiveness diminishes under highly aggressive acidic exposure (Torres and Sanjuán, 2017).

Limited but promising research indicates that LC3 systems may offer improved resistance to acid attack relative to OPC concrete due to reduced portlandite content and dense microstructure. However, systematic studies evaluating long-term acid resistance of LC3 concretes are scarce, highlighting a significant research gap.

CONCLUSIONS

SCMs Improve Concrete Durability: The incorporation of supplementary cementitious materials significantly enhances concrete durability in aggressive environments. Fly ash, GGBS, silica fume, metakaolin, RHA, and LC3 contribute to pore refinement, reduced permeability, and formation of additional hydration products, which collectively slow the ingress of aggressive agents.

Chloride and Sulphate Resistance: SCMs, particularly GGBS, silica fume, and LC3, substantially improve resistance to chloride ingress and sulphate attack by reducing calcium hydroxide content, increasing chloride binding capacity, and lowering the availability of reactive aluminates. Fly ash also contributes positively, though its performance depends on replacement level and curing conditions.

Carbonation Performance: High-volume fly ash and slag concretes may exhibit increased carbonation depth due to reduced portlandite content and lower buffering capacity, whereas silica fume, metakaolin, and LC3 improve carbonation resistance through microstructural densification. Adequate curing and mixture optimization are essential to mitigate carbonation susceptibility.

Acid Resistance: Acid attack remains a challenge for concrete structures, but SCMs such as GGBS, metakaolin, RHA, and LC3 enhance resistance by reducing calcium hydroxide content and densifying the microstructure. Nonetheless, no cementitious material is entirely resistant to strong acids, and performance is highly dependent on exposure severity.

Influencing Factors: Durability performance is affected by multiple factors, including SCM type, chemical composition, fineness, replacement level, curing regime, water-to-binder ratio, and environmental exposure. A holistic understanding of these factors is essential for the effective application of SCMs in aggressive environments.

Research Gaps: Despite advances, long-term field data, particularly for LC3 and RHA under severe aggressive conditions, remain limited. Future research should focus on service life prediction models, synergistic effects of SCM combinations, and validation under realistic exposure conditions.

Sustainability Implications: SCM incorporation not only enhances durability but also reduces clinker content, lowering CO_2 emissions and contributing to sustainable construction. Materials like LC3 represent a promising pathway for durable, low-carbon infrastructure.

Overall, the use of SCMs in concrete offers a dual benefit of improved durability and sustainability, but careful material selection, mixture design, and exposure-specific performance evaluation are critical to achieving long-term structural resilience.

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