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Durability Enhancement and Sustainability Assessment of M35 Recycled Aggregate and Geopolymer Concrete Incorporating Crystalline Admixtures

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Abstract

The construction industry is undergoing a paradigm shift towards sustainable and low-carbon materials owing to the increasing demand for environmentally responsible infrastructure, depletion of natural resources, and the significant contribution of Ordinary Portland Cement (OPC) production to global carbon dioxide (CO_2) emissions. Recycled Aggregate Concrete (RAC) and Geopolymer Concrete (GPC) have emerged as promising alternatives to conventional concrete; however, their widespread structural application remains constrained by concerns related to long-term durability, permeability, and aggressive environmental exposure. Although crystalline admixtures (CAs) have demonstrated the ability to improve concrete durability through pore refinement and self-sealing mechanisms, comprehensive comparative studies evaluating their performance in both recycled aggregate concrete and Geopolymer concrete under identical experimental conditions are limited.

This study presents a comprehensive experimental investigation on the influence of crystalline admixtures on the mechanical performance, durability, and sustainability of M35 Recycled Aggregate Concrete (RAC) incorporating 60% Recycled Concrete Aggregate (RCA) and M35 Geopolymer Concrete (GPC) produced using a ternary binder comprising Class F Fly Ash (200 kg/m³), Ground Granulated Blast Furnace Slag (160 kg/m³), and Silica Fume (40 kg/m³). Crystalline admixtures were incorporated at dosages of 0%, 0.8%, and 1.0% (by binder weight). Concrete mixtures were proportioned in accordance with IS 10262:2019, while durability requirements complied with IS 456:2000. Experimental evaluation included workability, compressive strength, split tensile strength, flexural strength, water absorption, water permeability, Rapid Chloride Permeability Test (RCPT), carbonation resistance, sulphate resistance, and sustainability assessment.

For M35 Recycled Aggregate Concrete, the incorporation of 1.0% crystalline admixture produced the optimum overall performance, increasing the 28-day compressive strength by 18.4% compared with the control mixture, while reducing water permeability by 70%, rapid chloride permeability by 60%, carbonation depth by 53.3%, and sulphate expansion by 58.3%. These improvements are attributed to the formation of moisture-activated insoluble crystals within the capillary pore network, resulting in pore refinement, reduced permeability, and a stronger interfacial transition zone between recycled aggregates and the cementitious matrix.

For M35 Geopolymer Concrete, the optimum dosage of 1.0% crystalline admixture achieved a 56-day compressive strength of 48 MPa, reduced water absorption by approximately 35%, decreased the Rapid Chloride Permeability Test (RCPT) value to 600 Coulombs, and lowered carbonation depth by approximately 43%, while exhibiting excellent resistance to sulphate attack. The synergistic interaction between alkali-activated aluminosilicate gels and crystalline reaction products produced a denser and less permeable microstructure, thereby significantly enhancing long-term durability.

The sustainability assessment demonstrated that the incorporation of 60% recycled concrete aggregate conserved approximately 720 kg of natural coarse aggregate per cubic metre of concrete, while geopolymer concrete reduced Portland cement consumption by 50%, corresponding to an estimated reduction of 170 kg CO_2 emissions per cubic metre. Based on the measured improvements in durability parameters, the sustainable concrete systems are expected to provide a substantially longer service life with reduced maintenance requirements, thereby lowering life-cycle environmental impacts and improving infrastructure resilience.

The results demonstrate that the combined application of recycled aggregates, Geopolymer binders, supplementary cementitious materials, and crystalline admixtures provides an effective and practical strategy for producing high-performance, durable, and environmentally sustainable concrete. The novelty of this research lies in the comparative evaluation of crystalline admixtures in M35 recycled aggregate concrete and ternary-blend Geopolymer concrete under identical experimental conditions, while simultaneously establishing a quantitative relationship between durability enhancement and sustainability performance. The proposed concrete systems offer a technically feasible and environmentally responsible solution for the development of resilient, low-carbon infrastructure that supports circular economy principles and future sustainable construction practices.

Keywords: Recycled Aggregate Concrete; Geopolymer Concrete; Crystalline Admixture; Durability; Sustainability; Supplementary Cementitious Materials; Rapid Chloride Permeability; Carbonation Resistance; Low-Carbon Concrete; Circular Economy.

1.Introduction

1.1 Global challenge in sustainable Concrete Construction

Concrete is the most widely used construction material in the world because of its versatility, structural strength, durability, affordability, and ease of production. It forms the backbone of modern infrastructure, including residential and commercial buildings, bridges, highways, tunnels, dams, airports, ports, and industrial facilities. Continuous urbanization, rapid population growth, and expanding infrastructure investments have significantly increased the global demand for concrete, making it indispensable for economic development and societal well-being (Habert et al., 2020; United Nations Environment Programme, 2025).

The buildings and construction sector is one of the largest consumers of natural resources and energy worldwide. According to the latest Global Status Report for Buildings and Construction, the sector accounts for approximately 34% of global energy demand and 34% of global energy- and process-related CO_2 emissions, making it one of the largest contributors to climate change. Furthermore, cement and steel production together account for nearly 18% of global greenhouse gas emissions, emphasizing the urgent need for sustainable construction materials and practices (UNEP, 2025; International Energy Agency, 2025).

Among all construction materials, Ordinary Portland Cement (OPC) has the greatest environmental impact because of the energy-intensive clinker manufacturing process and the calcination of limestone. Cement manufacturing alone contributes approximately 7–8% of global anthropogenic CO_2 emissions, making it one of the largest industrial sources of greenhouse gases. As infrastructure development accelerates, particularly in developing countries, reducing clinker production and adopting low-carbon cementitious materials have become global research priorities (Andrew, 2019; Scrivener et al., 2018). Recent industry assessments continue to confirm the critical need for cement decarbonisation through clinker substitution, carbon capture technologies, and supplementary cementitious materials.

Another major sustainability concern is the extensive extraction of natural aggregates. Concrete production consumes billions of tonnes of sand and crushed stone annually, leading to depletion of riverbeds, quarry resources, and natural landscapes. Excessive quarrying and river sand mining contribute to habitat destruction, biodiversity loss, groundwater depletion, soil erosion, and alterations in river morphology. Simultaneously, rapid urban redevelopment and infrastructure replacement generate enormous quantities of construction and demolition waste (CDW), much of which is still disposed of in landfills instead of being recycled into new construction materials (European Commission, 2020; UNEP, 2025).

The environmental impacts of conventional concrete extend beyond carbon emissions. Cement manufacturing, aggregate processing, transportation, and construction activities contribute significantly to air pollution, water pollution, soil degradation, and noise pollution. Dust emissions from quarrying, crushing, batching, and demolition increase concentrations of particulate matter ($PM_{2.5}$ and PM_{10}), adversely affecting air quality and public health. Construction runoff containing cement particles, suspended solids, and alkaline compounds contaminates nearby water bodies, while excavation and mining activities disturb soil structure and accelerate land degradation. In addition, heavy construction machinery and demolition operations generate high levels of noise and vibration that affect both surrounding communities and ecosystems (European Environment Agency, 2023; UNEP, 2025).

Rapid urban expansion also contributes to large-scale land-use change and deforestation. Forests, agricultural land, wetlands, and natural ecosystems are increasingly converted into residential developments, transportation corridors, and industrial zones. Such land conversion reduces biodiversity, weakens natural carbon sequestration capacity, alters hydrological cycles, and accelerates soil erosion. These cumulative environmental impacts demonstrate that conventional construction practices are no longer sustainable without integrating resource-efficient and environmentally responsible technologies (Intergovernmental Panel on Climate Change, 2023; FAO, 2022).

Recognizing these challenges, international organizations have emphasized the transition toward sustainable and low-carbon construction through the United Nations Sustainable Development Goals (SDGs), the Paris Agreement, and global Net Zero initiatives. In particular, SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) promote resource-efficient construction, waste minimization, circular economy principles, and reductions in greenhouse gas emissions. Recent international roadmaps further emphasize that achieving carbon neutrality in the construction sector requires substantial reductions in the embodied carbon of construction materials in addition to improving operational energy efficiency.

In response to these global challenges, research has increasingly focused on the development of sustainable concrete technologies capable of reducing environmental impacts while maintaining or improving structural performance. Strategies such as the incorporation of Recycled Concrete Aggregates (RCA), Supplementary Cementitious Materials (SCMs), Geopolymer Concrete (GPC), and Crystalline Admixtures (CA) have demonstrated considerable potential for lowering carbon emissions, conserving natural resources, extending service life, and enhancing durability. These technologies support the principles of the circular economy, in which construction waste is transformed into valuable resources while minimizing landfill disposal and reducing dependence on virgin raw materials (Habert et al., 2020; World Green Building Council, 2023; UNEP, 2025).

Accordingly, the construction industry is transitioning from conventional strength-based concrete design to a performance-based sustainability approach, where mechanical performance, durability, service life, resource efficiency, embodied carbon, and life-cycle environmental impacts are considered simultaneously. Developing durable, low-carbon, and resource-efficient concrete materials has therefore become essential for achieving resilient infrastructure while supporting global climate goals and sustainable development.

1.2 Recycled Aggregates Concrete for sustainable Infrastructure

The rapid growth of urbanization, infrastructure redevelopment, and population expansion has resulted in a substantial increase in construction and demolition waste (CDW) worldwide. Demolished concrete constitutes the largest fraction of CDW, much of which is disposed of in landfills despite possessing significant potential for recycling and reuse. The disposal of CDW not only occupies valuable landfill space but also contributes to environmental pollution, increased transportation costs, and the depletion of natural resources. Consequently, the recycling of demolished concrete into Recycled Concrete Aggregate (RCA) has emerged as an effective strategy for promoting sustainable construction and supporting circular economy principles (European Commission, 2020; UNEP, 2025).

Recycled Aggregate Concrete (RAC) is produced by replacing natural coarse aggregates partially or completely with recycled concrete aggregates obtained from demolished concrete structures. The utilization of RCA significantly reduces the demand for virgin aggregates, minimizes quarrying activities, conserves natural resources, and lowers greenhouse gas emissions associated with aggregate extraction and transportation. Furthermore, the reuse of construction waste contributes to sustainable waste management and reduces the environmental burden imposed on landfills, making RAC an attractive alternative for sustainable infrastructure development (Silva et al., 2014; Zhao et al., 2023).

Recent studies have demonstrated that RAC can achieve satisfactory structural performance when appropriate material processing, mix proportioning, and quality control measures are adopted. Mechanical properties such as compressive strength, split tensile strength, and flexural strength comparable to conventional concrete have been reported for RAC containing moderate levels of recycled aggregate replacement. However, the performance of RAC depends significantly on the quality of recycled aggregates, particularly the amount of adhered mortar, particle shape, crushing process, and water absorption characteristics (Luo et al., 2022; Li et al., 2024).

One of the primary challenges associated with RAC is the presence of residual adhered mortar on recycled aggregates. This adhered mortar increases aggregate porosity, water absorption, and microcrack density, resulting in a weaker Interfacial Transition Zone (ITZ) between the recycled aggregate and the new cement paste. Consequently, RAC generally exhibits higher permeability, increased shrinkage, reduced elastic modulus, and lower durability than conventional concrete, especially at high recycled aggregate replacement levels (Silva et al., 2014; Guo et al., 2018; Zhao et al., 2024).

Durability has therefore become the most critical factor governing the long-term performance of recycled aggregate concrete. The interconnected pore structure associated with recycled aggregates facilitates the ingress of water, chlorides, sulphate's, and carbon dioxide, thereby accelerating reinforcement corrosion, carbonation, sulphate attack, freeze–thaw deterioration, and alkali–silica reaction. Recent investigations have shown that permeability-related properties provide a more reliable indication of the long-term service life of RAC than compressive strength alone (Luo et al., 2022; Akbulut et al., 2025).

To overcome these limitations, considerable research has focused on improving the microstructure of RAC through the incorporation of Supplementary Cementitious Materials (SCMs) such as Fly Ash, Ground Granulated Blast Furnace Slag (GGBS), Silica Fume, Metakaolin, and Calcined Clay. These materials participate in pozzolanic and latent hydraulic reactions, consuming calcium hydroxide and producing additional calcium silicate hydrate (C–S–H) gel. The formation of secondary hydration products refines the pore structure, strengthens the ITZ, reduces permeability, and significantly improves the durability of recycled aggregate concrete (Lothenbach et al., 2011; Thomas, 2013; Kumar et al., 2024).

In addition to SCMs, recent research has explored advanced treatment methods for recycled aggregates, including carbonation treatment, Nano-silica coating, polymer impregnation, microbial treatment, and surface densification techniques. These approaches reduce water absorption, improve aggregate quality, strengthen the old mortar, and enhance the bond between recycled aggregates and the cement matrix. Carbonation treatment, in particular, has demonstrated considerable potential for reducing porosity while simultaneously capturing atmospheric carbon dioxide, thereby contributing to both durability enhancement and carbon sequestration (Zhang et al., 2023; Li et al., 2024).

From an environmental perspective, RAC contributes significantly to the principles of the circular economy by transforming construction waste into valuable construction materials. Every cubic metre of concrete incorporating recycled aggregates conserves natural aggregate resources, reduces landfill disposal, lowers transportation-related emissions, and minimizes environmental degradation associated with quarrying activities. Life Cycle Assessment (LCA) studies have consistently reported lower embodied energy and reduced carbon emissions for RAC compared with conventional concrete, particularly when combined with SCMs and optimized mix designs (Habert et al., 2020; World Green Building Council, 2023; UNEP, 2025).

Despite these environmental and engineering advantages, several challenges continue to limit the widespread structural application of RAC. Variability in recycled aggregate quality, lack of standardized processing methods, inconsistent national specifications, and limited long-term field performance data remain major barriers to broader implementation. Moreover, many published studies have focused primarily on mechanical properties while providing comparatively limited information regarding durability enhancement using advanced chemical admixtures under identical testing conditions (Akbulut et al., 2025; Zhao et al., 2024).

Therefore, further research is required to develop durable and sustainable recycled aggregate concrete by integrating recycled aggregates with supplementary cementitious materials and advanced durability-enhancing technologies. Among these technologies, crystalline admixtures have attracted increasing attention because of their ability to refine pore structure, reduce permeability, promote self-sealing of microcracks, and improve long-term durability. However, comprehensive comparative investigations evaluating the influence of crystalline admixtures in M35 Recycled Aggregate Concrete containing 60% RCA under identical experimental conditions remain limited. Addressing this research gap is essential for developing reliable, durable, and environmentally sustainable concrete suitable for future resilient infrastructure.

1.3 Geopolymer Concrete and Supplementary Cementitious Materials

The urgent need to reduce greenhouse gas emissions associated with Portland cement production has accelerated research into alternative low-carbon binder systems. Among the various sustainable technologies, Geopolymer Concrete (GPC) has emerged as one of the most promising alternatives to Ordinary Portland Cement (OPC) concrete due to its significantly lower carbon footprint, superior durability, and effective utilization of industrial by-products. Unlike conventional cement-based concrete, geopolymer concrete relies on the alkali activation of aluminosilicate-rich materials such as Class F Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Metakaolin (MK), and Silica Fume (SF) to produce a hardened binder through the Geopolymerization process rather than cement hydration (Davidovits, 1991; Provis & van Deventer, 2014; Zhang et al., 2023).

Geopolymerization is a chemical process involving the dissolution of silica (SiO_2) and alumina (Al_2O_3) from aluminosilicate precursor materials in highly alkaline environments, followed by polycondensation reactions that produce a three-dimensional sodium aluminosilicate hydrate (N–A–S–H) gel network. In calcium-rich systems containing GGBS, additional calcium aluminosilicate hydrate (C–A–S–H) and calcium silicate hydrate (C–S–H) gels are formed, resulting in a denser microstructure and improved early-age strength. Compared with OPC hydration products, Geopolymer gels exhibit lower porosity, higher chemical stability, and superior resistance to aggressive environmental conditions (Duxson et al., 2007; Provis, 2018; Akbulut et al., 2025).

Among the commonly used precursor materials, Class F Fly Ash is widely utilized because of its high silica and alumina contents, spherical particle morphology, and excellent workability characteristics. However, fly ash-based Geopolymer concrete generally exhibits relatively slow strength development under ambient curing conditions. To overcome this limitation, Ground Granulated Blast Furnace Slag (GGBS) is frequently incorporated because of its reactive calcium content, which accelerates Geopolymerization and significantly enhances early-age strength, matrix densification, and durability (Fernández-Jiménez & Palomo, 2005; Rashad, 2013; Li et al., 2024).

The incorporation of Silica Fume as an additional supplementary cementitious material has attracted considerable attention in recent years. Owing to its ultrafine particle size and high amorphous silica content, silica fume functions both as a micro filler and as a highly reactive pozzolanic material. It effectively fills micro voids, refines the pore structure, enhances the interfacial transition zone (ITZ), and promotes additional gel formation, thereby improving compressive strength, reducing permeability, and increasing resistance to chloride penetration and carbonation. Recent investigations have demonstrated that ternary Geopolymer systems incorporating Fly Ash, GGBS, and Silica Fume outperform binary binder systems in terms of mechanical properties, durability, and long-term dimensional stability (Ye et al., 2017; Zhang et al., 2023; Kumar et al., 2024).

One of the principal advantages of geopolymer concrete is its excellent durability. The dense aluminosilicate gel network significantly restricts the transport of water, chlorides, sulphate's, and carbon dioxide through the concrete matrix, thereby reducing reinforcement corrosion and extending structural service life. Numerous studies have reported that geopolymer concrete exhibits lower water absorption, reduced chloride permeability, improved sulphate resistance, enhanced acid resistance, and superior fire resistance compared with conventional OPC concrete (Shi et al., 2011; Provis, 2018; Luo et al., 2022; Akbulut et al., 2025).

The environmental benefits of geopolymer concrete are equally significant. Since Geopolymer binders utilize industrial by-products instead of clinker-based cement, they substantially reduce embodied carbon emissions associated with concrete production. Several Life Cycle Assessment (LCA) studies have reported that geopolymer concrete can reduce CO_2 emissions by 40–80%, depending on the precursor materials, alkaline activator composition, transportation distance, and curing method. In addition, the utilization of Fly Ash and GGBS diverts industrial waste from landfills, reduces the demand for virgin raw materials, and supports circular economy principles and sustainable resource utilization (Habert et al., 2020; Ouellet-Plamondon & Habert, 2015; UNEP, 2025).

Despite these advantages, several challenges continue to limit the large-scale implementation of Geopolymer concrete. Variations in fly ash composition, availability of high-quality precursor materials, handling of alkaline activators, lack of universally accepted design standards, and limited long-term field performance data remain significant barriers to commercialisation. Furthermore, most published studies have focused on optimizing geopolymer binder chemistry, while comparatively few investigations have evaluated the combined influence of crystalline admixtures on the durability and sustainability of geopolymer concrete under identical experimental conditions (Provis & van Deventer, 2014; Zhang et al., 2023; Li et al., 2024).

Recent research indicates that incorporating crystalline admixtures into geopolymer concrete may further refine pore structure, reduce permeability, and improve resistance to chloride ingress, carbonation, and sulphate attack through additional pore-blocking mechanisms. However, experimental evidence regarding the interaction between crystalline reaction products and geopolymer gel phases remains limited, particularly for ternary-blend geopolymer systems containing Fly Ash, GGBS, and Silica Fume. Moreover, direct comparative studies evaluating crystalline admixtures in both Recycled Aggregate Concrete (RAC) and Geopolymer Concrete (GPC) under identical experimental conditions are scarce.

Therefore, further research is required to investigate the synergistic effects of supplementary cementitious materials and crystalline admixtures on the mechanical performance, durability, and sustainability of geopolymer concrete. Such investigations will contribute to the development of durable, low-carbon, and resource-efficient concrete systems capable of meeting future infrastructure demands while supporting global sustainability and Net Zero objectives.

1.4 Durability Enhancement Using Crystalline Admixtures

The long-term performance of reinforced concrete structures is governed primarily by their durability rather than their compressive strength. Modern concrete structures are continuously exposed to aggressive environmental conditions, including marine environments, industrial pollutants, sulphate-bearing soils, freeze–thaw cycles, and carbonation. These exposure conditions accelerate the ingress of water, chloride ions, sulphate's, and carbon dioxide through interconnected capillary pores and microcracks, leading to reinforcement corrosion, chemical deterioration, and premature structural failure. Consequently, improving concrete durability has become one of the principal objectives in the development of sustainable and resilient infrastructure (Neville, 2011; Thomas, 2013; Habert et al., 2020).

Concrete deterioration is primarily controlled by its permeability. The interconnected capillary pore network formed during cement hydration acts as the principal pathway for the transport of moisture and aggressive ions. As permeability increases, chloride diffusion, sulphate attack, carbonation, and alkali–silica reaction (ASR) occur more rapidly, significantly reducing the service life of reinforced concrete structures. Therefore, refining the pore structure and reducing permeability have become the most effective strategies for improving long-term durability (Lothenbach et al., 2011; Mehta & Monteiro, 2014; Zhang et al., 2023).

Among the various durability-enhancing technologies, crystalline admixtures (CA) have attracted considerable attention because of their ability to provide permanent waterproofing through moisture-activated chemical reactions. Unlike conventional hydrophobic waterproofing admixtures that mainly reduce surface water absorption, crystalline admixtures react with unhydrated cement particles, calcium hydroxide, and moisture present within the concrete matrix to produce insoluble needle-shaped crystalline products. These crystals grow progressively within capillary pores, voids, and microcracks, forming an interconnected crystalline network that blocks the movement of water and aggressive ions while still permitting water vapour diffusion (ACI 212.3R-16; Richardson, 2008; Zhao et al., 2024).

The effectiveness of crystalline admixtures is based on their self-sealing mechanism. During cement hydration, a portion of the cement remains unhydrated within the hardened concrete matrix. Whenever moisture penetrates the concrete, the active chemicals present in crystalline admixtures react with these unhydrated cement particles and calcium hydroxide to generate additional insoluble crystalline products. This process continues throughout the service life of the concrete whenever water becomes available, enabling the material to seal newly formed microcracks and continuously reduce permeability. Recent studies have reported that crystalline admixtures can effectively seal cracks up to approximately 0.4 mm, thereby significantly improving water tightness and extending the service life of concrete structures (ACI 212.3R-16; Zhang et al., 2023; Li et al., 2024).

In addition to improving impermeability, crystalline admixtures contribute to the refinement of the concrete microstructure. The formation of additional crystalline products reduces capillary pore connectivity, increases matrix density, and strengthens the interfacial transition zone (ITZ) between aggregates and the cement paste. As a result, concrete containing crystalline admixtures exhibits lower water absorption, reduced water permeability, lower Rapid Chloride Permeability Test (RCPT) values, improved carbonation resistance, enhanced sulphate resistance, and better freeze–thaw durability compared with conventional concrete. Several recent investigations have demonstrated significant reductions in chloride ion diffusion and water permeability due to the pore-blocking action of crystalline admixtures (Luo et al., 2022; Kumar et al., 2024; Akbulut et al., 2025).

The application of crystalline admixtures becomes particularly important in Recycled Aggregate Concrete (RAC) because recycled concrete aggregates contain residual adhered mortar with higher porosity and water absorption than natural aggregates. The porous nature of recycled aggregates results in a weaker interfacial transition zone and higher permeability, thereby increasing the susceptibility of RAC to chloride ingress, carbonation, and sulphate attack. Crystalline admixtures mitigate these deficiencies by sealing interconnected pores, reducing moisture transport, strengthening the ITZ, and improving the overall durability of recycled aggregate concrete (Silva et al., 2014; Zhao et al., 2024).

Similarly, although Geopolymer Concrete (GPC) inherently possesses a denser microstructure than conventional Portland cement concrete, recent studies have suggested that crystalline admixtures can provide additional durability benefits by further reducing pore connectivity and improving resistance to aggressive environments. The interaction between crystalline reaction products and Geopolymeric gel phases contributes to enhanced water tightness, lower chloride permeability, and improved carbonation resistance. However, experimental studies investigating crystalline admixtures in geopolymer concrete remain limited, particularly for ternary-blend systems incorporating Fly Ash, GGBS, and Silica Fume (Provis, 2018; Li et al., 2024; Zhang et al., 2023).

From a sustainability perspective, crystalline admixtures contribute not only by improving waterproofing but also by significantly extending the service life of concrete structures. Improved durability reduces the frequency of maintenance, repair, and rehabilitation activities, thereby decreasing the consumption of construction materials, reducing life-cycle carbon emissions, minimizing maintenance costs, and conserving natural resources. Consequently, crystalline admixtures are increasingly recognized as an integral component of sustainable concrete technology and play an important role in achieving circular economy objectives and low-carbon infrastructure development (Habert et al., 2020; World Green Building Council, 2023; UNEP, 2025).

Despite the considerable progress reported in recent literature, several knowledge gaps remain. Most published investigations have evaluated crystalline admixtures in conventional Portland cement concrete, whereas comparatively few studies have systematically investigated their performance in high-volume Recycled Aggregate Concrete (60% RCA) and ternary-blend Geopolymer Concrete under identical experimental conditions. Furthermore, limited research has simultaneously evaluated the influence of crystalline admixtures on mechanical performance, durability characteristics, and sustainability indicators using a unified experimental framework. Addressing these research gaps forms the basis of the present investigation, which aims to identify the optimum crystalline admixture dosage for producing durable and environmentally sustainable M35 recycled aggregate and geopolymer concrete.

1.5 Durability–Sustainability Relationship

From a sustainability perspective, durability plays a decisive role in determining the environmental performance of concrete throughout its service life. Sustainable construction should not be evaluated solely on the basis of embodied carbon during material production but also by considering service-life extension, reduced maintenance, lower repair frequency, and improved life-cycle performance (Habert et al., 2020; World Green Building Council, 2023). Increasing the durability of concrete directly reduces future material consumption, maintenance-related emissions, operational disruptions, and infrastructure replacement costs. Consequently, durability improvement has become one of the most effective strategies for reducing the overall environmental footprint of concrete structures (Scrivener et al., 2018; UNEP, 2023).

Furthermore, integrating recycled concrete aggregates, supplementary cementitious materials, geopolymer technology, and crystalline admixtures strongly supports the principles of the circular economy by simultaneously reducing construction waste, conserving virgin natural aggregates, minimizing Portland cement consumption, and extending infrastructure service life (European Commission, 2020; World Business Council for Sustainable Development, 2023). Such integrated approaches are increasingly recognized as essential for achieving global climate targets, net-zero construction, and sustainable infrastructure development.

Despite substantial advances in recycled aggregate concrete, Geopolymer concrete, and crystalline admixture technology, most previous investigations have evaluated these materials independently or focused on a single performance parameter. Comprehensive comparative studies simultaneously investigating the influence of crystalline admixtures on M35 recycled aggregate concrete containing 60% recycled coarse aggregate and ternary-blend geopolymer concrete under identical experimental conditions, while correlating mechanical performance, durability enhancement, and sustainability benefits, remain limited. This research gap forms the basis of the present investigation, which is addressed in the following section through the research objectives, novelty, and scope of the study.

1.6 Research Objectives

The primary objective of this research is to evaluate the effectiveness of crystalline admixtures in enhancing the mechanical performance, durability, and sustainability of M35 Recycled Aggregate Concrete (RAC) incorporating 60% Recycled Concrete Aggregate (RCA) and M35 Geopolymer Concrete (GPC) produced using a ternary binder system consisting of Class F Fly Ash, Ground Granulated Blast Furnace Slag (GGBS), and Silica Fume. The study aims to identify the optimum crystalline admixture dosage capable of producing durable, low-carbon, and environmentally sustainable concrete suitable for modern infrastructure applications.

The specific objectives of the research are as follows:

1. To develop M35 Recycled Aggregate Concrete (RAC) and M35 Geopolymer Concrete (GPC) incorporating crystalline admixtures at dosages of 0%, 0.8%, and 1.0% by binder weight in accordance with the relevant Indian Standards and established geopolymer concrete mix design procedures.
2. To evaluate the fresh properties of RAC and GPC by determining workability through slump tests and assessing the influence of crystalline admixture dosage on fresh concrete behaviour.
3. To investigate the mechanical properties of the developed concrete mixes by determining compressive strength, split tensile strength, and flexural strength at different curing ages and identifying the optimum crystalline admixture dosage.
4. To assess the durability performance of RAC and GPC by conducting water absorption, water permeability, Rapid Chloride Permeability Test (RCPT), carbonation resistance, and sulphate resistance tests in order to quantify the improvement in resistance to aggressive environmental conditions.
5. To investigate the influence of crystalline admixtures on the microstructural refinement of concrete by correlating improvements in permeability-related properties with pore refinement, crack-sealing mechanisms, and enhancement of the Interfacial Transition Zone (ITZ).
6. To compare the engineering performance of RAC and GPC under identical experimental conditions in order to identify the most durable and sustainable concrete system for structural applications.
7. To quantify the sustainability benefits associated with recycled aggregate utilization, supplementary cementitious materials, geopolymer binders, and crystalline admixtures in terms of:
    - Reduction in Portland cement consumption.
    - Conservation of natural aggregate resources.
    - Reduction in embodied carbon emissions.
    - Utilization of industrial by-products and construction waste.
    - Contribution towards circular economy principles.
8. To establish the relationship between durability enhancement and sustainability performance by correlating improvements in durability parameters with anticipated service-life extension, maintenance reduction, and life-cycle environmental benefits.

9. To determine the optimum crystalline admixture dosage capable of simultaneously maximising mechanical performance, durability, and sustainability in both recycled aggregate concrete and geopolymer concrete.
10. To provide practical recommendations for the application of crystalline admixtures in sustainable concrete technologies suitable for durable, resilient, and low-carbon infrastructure development.

Expected Outcomes

The successful completion of this research is expected to:

- Develop durable and sustainable M35 recycled aggregate concrete and geopolymer concrete incorporating crystalline admixtures.
- Identify the optimum crystalline admixture dosage for maximizing mechanical and durability performance.
- Demonstrate the effectiveness of crystalline admixtures in reducing permeability, chloride ingress, carbonation, and sulphate attack.
- Quantify the sustainability benefits achieved through recycled aggregate utilization, geopolymer binders, and supplementary cementitious materials.
- Establish a direct relationship between durability enhancement and sustainability performance.
- Provide practical guidance for the adoption of sustainable concrete in infrastructure projects supporting circular economy and Net Zero objectives.

1.7 Novelty of the Study

The present research contributes to the advancement of sustainable concrete technology by providing a comprehensive comparative evaluation of M35 Recycled Aggregate Concrete (RAC) and M35 Geopolymer Concrete (GPC) incorporating crystalline admixtures under identical experimental conditions. Although extensive research has been conducted separately on recycled aggregate concrete, geopolymer concrete, supplementary cementitious materials, and crystalline admixtures, relatively few studies have investigated their combined influence on mechanical performance, durability, and sustainability within a unified experimental framework (Habert et al., 2020; Zhao et al., 2024).

The first novelty of this research lies in the direct comparison of two sustainable concrete systems—M35 Recycled Aggregate Concrete containing 60% Recycled Concrete Aggregate (RCA) and M35 Geopolymer Concrete incorporating a ternary binder system consisting of Class F Fly Ash, Ground Granulated Blast Furnace Slag (GGBS), and Silica Fume. Both concrete systems are evaluated using identical testing procedures, curing conditions, and crystalline admixture dosages, enabling a reliable comparison of their engineering performance and durability.

The second novel contribution is the systematic investigation of crystalline admixture dosages (0%, 0.8%, and 1.0% by binder weight) in both RAC and GPC. Previous studies have generally focused on conventional Portland cement concrete or have evaluated crystalline admixtures in only one concrete system. The present investigation provides a direct assessment of the effectiveness of crystalline admixtures in improving recycled aggregate and Geopolymer concrete under identical experimental conditions, allowing the optimum dosage to be identified for sustainable concrete applications.

A further innovation of this research is the integrated evaluation of mechanical performance and durability. Rather than relying solely on compressive strength, the study investigates fresh concrete properties together with compressive strength, split tensile strength, flexural strength, water absorption, water permeability, Rapid Chloride Permeability Test (RCPT), carbonation resistance, and sulphate resistance. This comprehensive experimental programme provides a more complete understanding of the influence of crystalline admixtures on long-term concrete performance.

The study also introduces an integrated durability–sustainability assessment framework, which links improvements in durability parameters with sustainability indicators. The sustainability assessment includes the conservation of natural coarse aggregates through the utilization of 60% recycled concrete aggregate, reduction in Portland cement consumption through geopolymer technology, utilization of industrial by-products such as Fly Ash, GGBS, and Silica Fume, estimation of embodied carbon reduction, and the anticipated extension of service life resulting from improved durability. Unlike many previous studies that evaluate environmental and engineering performance independently, the present work establishes a quantitative relationship between durability enhancement and sustainability performance.

Another significant contribution is the investigation of the combined effect of supplementary cementitious materials and crystalline admixtures on pore refinement and microstructural densification. The research explains how secondary hydration products in recycled aggregate concrete and geopolymer gel formation in geopolymer concrete interact with crystalline reaction products to reduce permeability, strengthen the Interfacial Transition Zone (ITZ), and improve resistance to aggressive environmental exposure.

Furthermore, this research contributes to the implementation of circular economy principles by integrating recycled construction and demolition waste with industrial by-products to develop high-performance, low-carbon concrete. The proposed concrete systems promote resource conservation, waste utilization, reduction of greenhouse gas emissions, and sustainable infrastructure development, thereby supporting international sustainability initiatives including the United Nations Sustainable Development Goals (SDGs) and Net Zero carbon strategies (UNEP, 2025; World Green Building Council, 2023).

Finally, the findings of this research are expected to provide practical recommendations for engineers, researchers, infrastructure agencies, and policymakers regarding the application of crystalline admixtures in sustainable concrete systems. The outcomes will contribute to the development of durable, environmentally responsible, and economically viable concrete suitable for long-service-life infrastructure in aggressive environmental conditions.

Key Novel Contributions of the Present Study

1. Comparative evaluation of M35 Recycled Aggregate Concrete (60% RCA) and M35 Geopolymer Concrete under identical experimental conditions.
2. Investigation of three crystalline admixture dosages (0%, 0.8%, and 1.0%) to determine the optimum dosage for sustainable concrete.
3. Comprehensive assessment of fresh properties, mechanical properties, durability, and sustainability within a single experimental programme.
4. Evaluation of the combined effects of Fly Ash, GGBS, Silica Fume, and Crystalline Admixtures on pore refinement, permeability reduction, and ITZ improvement.
5. Development of an integrated durability–sustainability assessment framework linking engineering performance with environmental benefits.
6. Quantification of sustainability indicators, including:
    - Natural aggregate conservation.
    - Portland cement reduction.
    - Utilization of recycled and industrial waste materials.
    - Embodied carbon reduction.
    - Potential service-life extension.
7. Contribution to circular economy implementation and the development of durable, low-carbon concrete for resilient infrastructure.

2. Literature Review

2.1 Global Construction Industry: Economic Growth and Sustainability Challenges

2.1.1 Introduction

The construction industry is one of the largest and most influential sectors of the global economy, playing a fundamental role in economic development, urbanization, industrialization, and infrastructure expansion. It encompasses the planning, design, construction, operation, maintenance, and rehabilitation of residential buildings, commercial complexes, transportation networks, bridges, tunnels, airports, ports, dams, power plants, and other civil engineering infrastructure. The sector supports socioeconomic growth by creating employment opportunities, improving connectivity, enhancing industrial productivity, and facilitating sustainable urban development (Habert et al., 2020; United Nations Environment Programme [UNEP], 2024).

Globally, the construction sector contributes approximately 11–13% of the world's Gross Domestic Product (GDP) and supports millions of direct and indirect jobs through engineering, manufacturing, transportation, material production, and associated service industries. Rapid population growth, urban migration, industrialization, and government investments in infrastructure continue to accelerate construction activities, particularly in developing economies such as India, China, Indonesia, Brazil, and several African nations. According to the United Nations, approximately 68% of the global population is projected to reside in urban areas by 2050, creating unprecedented demand for housing, transportation systems, healthcare facilities, educational institutions, and public infrastructure (United Nations, 2018; World Bank, 2023).

Concrete remains the most widely used construction material because of its versatility, high compressive strength, durability, fire resistance, availability of raw materials, and relatively low production cost. It is estimated that more than 30 billion tonnes of concrete are produced annually, making it the second most consumed material on Earth after water (Scrivener et al., 2018; Habert et al., 2020). However, this enormous production volume requires substantial quantities of cement, aggregates, water, and energy, leading to significant environmental challenges, including greenhouse gas emissions, depletion of natural resources, and generation of construction and demolition waste (UNEP, 2024).

The increasing demand for infrastructure has intensified concerns regarding the sustainability of conventional construction practices. Cement manufacturing, aggregate extraction, transportation, and construction activities contribute substantially to carbon emissions, energy consumption, and environmental degradation. Consequently, international organizations, governments, and researchers have emphasized the development of sustainable construction materials capable of reducing embodied carbon while maintaining structural performance and durability. Sustainable concrete technologies, including recycled aggregate concrete (RAC), geopolymer concrete (GPC), supplementary cementitious materials (SCMs), and crystalline admixtures (CA), have therefore attracted considerable research attention as potential solutions to these global challenges (Habert et al., 2020; World Green Building Council, 2023; UNEP, 2024).

2.1.2 Global Construction Growth and Infrastructure Demand

The global construction industry has experienced continuous expansion over the past two decades due to rapid urbanization, industrialization, population growth, and economic development. According to the United Nations Department of Economic and Social Affairs (UN DESA), the world's urban population is expected to increase from approximately 56% in 2021 to nearly 68% by 2050, resulting in significant demand for residential buildings, transportation infrastructure, industrial facilities, water supply systems, healthcare institutions, and educational facilities (United Nations, 2018).

Emerging economies are expected to account for the majority of future infrastructure investments. Countries such as India, China, Indonesia, Vietnam, and Brazil continue to implement large-scale infrastructure projects involving highways, metro rail systems, airports, ports, smart cities, renewable energy facilities, and industrial corridors. India's National Infrastructure Pipeline (NIP), Smart Cities Mission, Bharatmala Pariyojana, and PM Gati Shakti programme are examples of major initiatives aimed at improving transportation, logistics, and urban infrastructure while supporting long-term economic growth (Government of India, 2023).

The increasing demand for infrastructure has resulted in a corresponding rise in the consumption of construction materials. Cement production has exceeded 4 billion tonnes annually, while billions of tonnes of aggregates are extracted each year for concrete production. The extensive use of natural resources has intensified environmental concerns related to quarrying, river sand mining, biodiversity loss, land degradation, groundwater depletion, and ecosystem disturbance (Scrivener et al., 2018; UNEP, 2024).

Infrastructure development provides substantial economic and social benefits by improving transportation efficiency, industrial productivity, employment generation, public health, education, and quality of life. However, these benefits must be balanced against the environmental impacts associated with conventional construction practices. Consequently, the construction industry is undergoing a gradual transition from traditional resource-intensive practices toward sustainable construction methods that prioritize resource efficiency, waste reduction, carbon mitigation, and long-term durability (World Green Building Council, 2023; International Energy Agency [IEA], 2024).

2.1.3 Environmental Impact of Conventional Construction

The rapid expansion of the construction industry has significantly contributed to global economic development; however, it has also become one of the major drivers of environmental degradation. The construction sector consumes enormous quantities of natural resources, including limestone, sand, gravel, crushed stone, steel, timber, and water, while generating substantial greenhouse gas emissions and construction waste. According to the United Nations Environment Programme (UNEP), the buildings and construction sector accounted for approximately 34% of global energy demand and 37% of global energy- and process-related carbon dioxide (CO_2) emissions in 2022, making it one of the largest contributors to climate change (UNEP, 2024).

The environmental impacts associated with conventional construction occur throughout the entire life cycle of infrastructure, including raw material extraction, material processing, transportation, construction, operation, maintenance, demolition, and waste disposal. The extraction of limestone for cement production, quarrying of aggregates, and river sand mining significantly disturb ecosystems, alter natural landscapes, reduce biodiversity, and accelerate soil erosion. In addition, the manufacture of construction materials requires substantial amounts of thermal energy and electricity, most of which are still generated from fossil fuels, thereby increasing greenhouse gas emissions and environmental pollution (Habert et al., 2020; Scrivener et al., 2018).

Apart from carbon emissions, construction activities generate large quantities of dust, noise, wastewater, and solid waste. Dust generated during excavation, crushing, batching, transportation, and demolition contributes to increased concentrations of particulate matter ($PM_{2.5}$ and PM_{10}), adversely affecting air quality and public health. Construction runoff often contains suspended solids, cement particles, alkaline compounds, oils, and chemicals that contaminate nearby water bodies and negatively affect aquatic ecosystems. Similarly, heavy machinery used during construction and demolition generates high levels of noise and vibration, causing discomfort to nearby communities and disrupting wildlife habitats (European Environment Agency, 2023; UNEP, 2024).

Another major environmental concern is the extensive generation of Construction and Demolition Waste (CDW). Rapid urban redevelopment and replacement of aging infrastructure have resulted in millions of tonnes of concrete, masonry, steel, timber, asphalt, and other construction materials being discarded annually. Although concrete constitutes the largest fraction of CDW and possesses significant recycling potential, a considerable proportion is still disposed of in landfills instead of being reused as recycled construction materials. This practice increases landfill requirements, transportation costs, environmental pollution, and the depletion of natural aggregate resources (European Commission, 2020; Silva et al., 2014).

Growing environmental concerns have encouraged governments, researchers, and industry stakeholders to adopt sustainable construction practices that minimize resource consumption, reduce waste generation, and lower greenhouse gas emissions. Strategies such as the use of Recycled Concrete Aggregates (RCA), Supplementary Cementitious Materials (SCMs), Geopolymer Concrete (GPC), and durability-enhancing admixtures have demonstrated considerable potential for reducing the environmental impacts of conventional concrete while maintaining structural performance and extending service life (Habert et al., 2020; World Green Building Council, 2023).

2.1.4 Carbon Emissions from Cement Production

Ordinary Portland Cement (OPC) is the principal binding material used in concrete production and is responsible for a significant proportion of the environmental impacts associated with the construction industry. Cement manufacturing is an energy-intensive process involving the calcination of limestone and the production of clinker at temperatures exceeding 1450°C. During calcination, calcium carbonate ($CaCO_3$) decomposes into calcium oxide (CaO), releasing substantial quantities of carbon dioxide as a chemical by-product. In addition, large amounts of fossil fuels such as coal, petroleum coke, and natural gas are consumed to maintain the high kiln temperatures required for clinker formation (Scrivener et al., 2018).

Globally, cement production contributes approximately 7–8% of anthropogenic CO_2 emissions, making it one of the largest industrial sources of greenhouse gases (Andrew, 2019). Current global cement production exceeds 4 billion tonnes annually, and increasing infrastructure development is expected to further increase cement demand over the coming decades, particularly in rapidly developing countries. Without significant technological advancements and material innovations, continued dependence on Portland cement will make achieving international climate targets increasingly difficult (IEA, 2024; GCCA, 2024).

The carbon footprint of cement production originates from two principal sources. The first is process emissions, which account for approximately 60% of total emissions and result from the calcination of limestone during clinker production. The second is energy-related emissions, accounting for approximately

40%, which arise from the combustion of fossil fuels used to heat rotary kilns. Together, these processes make Portland cement one of the most carbon-intensive construction materials currently available (Scrivener et al., 2018; Habert et al., 2020).

In response to these environmental concerns, significant research efforts have focused on reducing cement-related emissions through clinker substitution, energy-efficient manufacturing, carbon capture and storage (CCS), utilization of supplementary cementitious materials, and the development of alternative binders such as geopolymer concrete. Among these approaches, the partial replacement of Portland cement with Fly Ash, Ground Granulated Blast Furnace Slag (GGBS), Silica Fume, and other industrial by-products has been widely recognized as one of the most practical and economically feasible strategies for reducing embodied carbon while simultaneously improving concrete durability (Provis & van Deventer, 2014; Habert et al., 2020; UNEP, 2024).

The transition towards low-carbon concrete technologies has therefore become a global research priority. Recent international initiatives such as the Global Cement and Concrete Association (GCCA) Roadmap to Net Zero Concrete and the UNEP Global Status Report for Buildings and Construction emphasize that substantial reductions in cement consumption, increased recycling of construction materials, and improvements in durability are essential for achieving carbon-neutral infrastructure by 2050 (GCCA, 2024; UNEP, 2024).

2.1.5 Natural Resource Depletion

The construction industry is one of the largest consumers of natural resources worldwide, utilizing enormous quantities of limestone, sand, gravel, crushed stone, clay, water, steel, and timber for the production of construction materials and infrastructure. Concrete production alone consumes billions of tonnes of natural aggregates annually, making it the largest consumer of raw materials after water. The continuous extraction of these resources has accelerated environmental degradation, resulting in habitat destruction, riverbank erosion, groundwater depletion, biodiversity loss, and irreversible alterations to natural ecosystems (UNEP, 2024; Habert et al., 2020).

Natural aggregates constitute approximately 70–80% of the volume of conventional concrete, and their increasing demand has intensified quarrying activities worldwide. Excessive extraction of river sand has disrupted river ecosystems, lowered groundwater tables, increased flood risks, and reduced aquatic biodiversity. Similarly, large-scale quarrying of crushed stone alters landscapes, generates dust and noise pollution, and contributes to soil degradation. Many countries have introduced stricter environmental regulations governing aggregate extraction because of growing concerns regarding the long-term availability of natural resources (Peduzzi, 2014; European Commission, 2020).

Water is another critical resource extensively consumed during concrete production, curing, aggregate washing, and construction activities. Increasing water scarcity in many regions of the world has encouraged researchers to investigate alternative materials and technologies capable of reducing water consumption while maintaining concrete performance. Consequently, the utilization of Recycled Concrete Aggregates (RCA), manufactured sand, industrial by-products, and Supplementary Cementitious Materials (SCMs) has become an important strategy for conserving natural resources and promoting sustainable construction (Thomas, 2013; UNEP, 2024).

2.1.6 Construction and Demolition Waste (CDW)

Construction and demolition activities generate substantial quantities of waste throughout the lifecycle of buildings and infrastructure. Construction and Demolition Waste (CDW) includes demolished concrete, masonry, bricks, asphalt, timber, metals, plastics, glass, and excavated soil. Rapid urban redevelopment, replacement of aging infrastructure, and increasing construction activities have significantly increased the generation of CDW worldwide. The European Commission estimates that CDW accounts for approximately 30–40% of the total solid waste generated globally, making it one of the largest waste streams in the construction sector (European Commission, 2020).

Among the various components of CDW, demolished concrete represents the largest fraction and possesses significant potential for recycling. However, a considerable proportion of demolished concrete is still disposed of in landfills rather than being processed into recycled construction materials. Landfilling of CDW not only occupies valuable land but also increases transportation costs, environmental pollution, and greenhouse gas emissions associated with waste handling and disposal (Silva et al., 2014; UNEP, 2024).

The recycling of demolished concrete into Recycled Concrete Aggregate (RCA) offers significant environmental and economic benefits. RCA reduces dependence on virgin natural aggregates, minimizes landfill disposal, lowers transportation-related emissions, conserves natural resources, and supports circular economy principles. Recent studies have demonstrated that properly processed RCA can be successfully utilized in structural concrete while maintaining satisfactory mechanical and durability performance when appropriate mix design and quality control procedures are adopted (Silva et al., 2014; Zhao et al., 2024).

2.1.7 Air, Water, Soil, and Noise Pollution

Construction activities contribute significantly to environmental pollution through the emission of airborne particulates, contamination of water resources, degradation of soil quality, and generation of excessive noise and vibration. Dust generated during quarrying, aggregate crushing, cement production, batching, transportation, and demolition increases concentrations of particulate matter ($PM_{2.5}$ and PM_{10}), adversely affecting respiratory health and reducing air quality in urban areas. Cement manufacturing also emits nitrogen oxides (NO_x), sulfur dioxide (SO_2), and other pollutants that contribute to acid rain and atmospheric pollution (European Environment Agency, 2023).

Water pollution associated with construction activities results primarily from runoff containing cement particles, suspended solids, alkaline compounds, oils, lubricants, and chemical admixtures. These pollutants contaminate nearby rivers, lakes, and groundwater resources, adversely affecting aquatic ecosystems and reducing water quality. Inadequate management of construction wastewater may also increase the alkalinity and turbidity of receiving water bodies (UNEP, 2024).

Construction operations also contribute to soil degradation through excavation, quarrying, mining, waste disposal, and heavy machinery movement. These activities disturb soil structure, accelerate erosion, reduce soil fertility, and increase sediment transport into nearby watercourses. Furthermore, heavy construction equipment, drilling, piling, blasting, and demolition operations generate high levels of noise and vibration, causing discomfort to nearby communities, reducing occupational health standards, and disturbing wildlife habitats (European Environment Agency, 2023).

The cumulative impacts of air, water, soil, and noise pollution emphasize the importance of adopting environmentally responsible construction practices, improving waste management, utilizing recycled materials, and implementing sustainable concrete technologies capable of reducing pollution throughout the infrastructure life cycle (World Green Building Council, 2023).

2.1.8 Land-Use Change and Deforestation

Rapid urbanization and infrastructure expansion have resulted in extensive land-use change worldwide. Forests, wetlands, agricultural land, and natural ecosystems are increasingly converted into residential developments, transportation corridors, industrial zones, and commercial infrastructure. Such land conversion significantly reduces biodiversity, weakens natural carbon sequestration capacity, alters hydrological cycles, and accelerates soil erosion (IPCC, 2023).

Deforestation associated with infrastructure development contributes directly to climate change by reducing carbon storage capacity and increasing atmospheric greenhouse gas concentrations. Quarrying activities for limestone and aggregates further disturb natural landscapes, affecting vegetation cover and ecological balance. Sustainable infrastructure development therefore requires greater emphasis on resource-efficient construction, recycling of demolition waste, and utilization of low-carbon construction materials capable of minimizing environmental impacts while supporting long-term economic development (FAO, 2022; IPCC, 2023).

2.1.9 Sustainable Development Goals (SDGs) and Net Zero Construction

The global transition toward sustainable construction is strongly aligned with the **United Nations Sustainable Development Goals (SDGs)** and international climate agreements aimed at achieving carbon neutrality. Sustainable concrete technologies directly contribute to several SDGs, particularly:

- **SDG 9 –** Industry, Innovation and Infrastructure, by promoting resilient and sustainable infrastructure.

- **SDG 11 –** Sustainable Cities and Communities, through durable and environmentally responsible construction.
- **SDG 12 –** Responsible Consumption and Production, by encouraging recycling, efficient resource utilization, and waste minimization.
- **SDG 13 –** Climate Action, by reducing greenhouse gas emissions and supporting low-carbon construction technologies (United Nations, 2015; UNEP, 2024).

International initiatives such as the Paris Agreement, the Global Cement and Concrete Association (GCCA) Net Zero Roadmap, and the International Energy Agency (IEA) Buildings and Construction Programme emphasize that reducing embodied carbon, increasing recycled material utilization, improving durability, and extending infrastructure service life are essential for achieving Net Zero emissions by 2050. Consequently, sustainable concrete technologies incorporating recycled aggregates, supplementary cementitious materials, geopolymer binders, and crystalline admixtures have become critical components of future resilient infrastructure development (GCCA, 2024; IEA, 2024; World Green Building Council, 2023).

Critical Analysis

The literature clearly demonstrates that the construction industry remains one of the largest contributors to greenhouse gas emissions, natural resource depletion, and environmental pollution despite its vital role in socioeconomic development. Although numerous investigations have focused on reducing the environmental impacts of concrete through recycled aggregates, supplementary cementitious materials, and alternative binders, most studies have evaluated these technologies independently. Limited research has integrated Recycled Concrete Aggregate (RCA), Geopolymer Concrete (GPC), Supplementary Cementitious Materials (SCMs), and Crystalline Admixtures (CA) within a single experimental framework to evaluate their combined effects on mechanical performance, durability, and sustainability. Furthermore, comparatively few studies have quantified the relationship between durability enhancement, service-life extension, embodied carbon reduction, and natural resource conservation. These limitations indicate a clear need for comprehensive investigations that simultaneously address engineering performance and environmental sustainability, thereby providing the foundation for the present research (Habert et al., 2020; Zhao et al., 2024; UNEP, 2024).

2.2 Sustainable Concrete Materials: Towards Low-Carbon and Circular Construction

2.2.1 Introduction to Sustainable Concrete

The construction industry is undergoing a paradigm shift from conventional material-intensive practices toward sustainable construction approaches that emphasize resource efficiency, environmental protection, and long-term infrastructure resilience. Among the various construction materials, concrete remains indispensable because of its versatility, structural performance, durability, and economic advantages. However, the extensive use of Ordinary Portland Cement (OPC) and natural aggregates has resulted in significant greenhouse gas emissions, depletion of natural resources, and environmental degradation. Consequently, the development of sustainable concrete materials has become one of the primary research priorities in civil engineering (Habert et al., 2020; UNEP, 2024).

Sustainable concrete may be defined as concrete designed to minimize environmental impacts throughout its life cycle while maintaining or improving structural performance, durability, and economic feasibility. Unlike conventional concrete, sustainable concrete incorporates environmentally friendly materials such as Recycled Concrete Aggregates (RCA), Supplementary Cementitious Materials (SCMs), industrial by-products, alternative binders, recycled water, and durability-enhancing admixtures. These materials reduce dependence on virgin resources, decrease carbon emissions, conserve natural ecosystems, and extend infrastructure service life, thereby supporting sustainable development principles (Mehta & Monteiro, 2014; Habert et al., 2020; World Green Building Council, 2023).

Modern sustainable concrete design is increasingly based on Life Cycle Thinking (LCT), which considers environmental impacts from raw material extraction through production, transportation, construction, operation, maintenance, rehabilitation, demolition, and recycling. This approach extends beyond reducing embodied carbon during manufacturing and emphasizes durability, service-life extension, maintenance reduction, and end-of-life resource recovery. Consequently, sustainable concrete contributes simultaneously to environmental protection, economic efficiency, and social development (ISO 14040, 2006; UNEP, 2024).

2.2.2 Circular Economy in Construction

The concept of the circular economy has emerged as one of the most effective strategies for improving sustainability within the construction industry. Unlike the traditional linear economic model based on "take–make–dispose", the circular economy promotes continuous utilization of materials through recycling, reuse, refurbishment, remanufacturing, and resource recovery. In the construction sector, this approach aims to minimize waste generation while maximizing the value of materials throughout the infrastructure life cycle (European Commission, 2020).

Construction and demolition waste (CDW) constitutes one of the largest waste streams worldwide. Demolished concrete, masonry, steel, timber, asphalt, and other construction materials possess significant potential for recycling. The conversion of demolished concrete into Recycled Concrete Aggregate (RCA) enables construction waste to be transformed into valuable engineering materials suitable for new concrete production. Similarly, industrial by-products such as Fly Ash, Ground Granulated Blast Furnace Slag (GGBS), and Silica Fume are increasingly utilized as supplementary cementitious materials, thereby reducing landfill disposal while conserving natural resources (Silva et al., 2014; European Commission, 2020).

The implementation of circular economy principles in concrete production provides multiple environmental benefits, including reduced consumption of virgin aggregates, lower cement demand, decreased greenhouse gas emissions, minimized landfill disposal, and improved resource efficiency. Recent Life Cycle Assessment (LCA) studies indicate that concrete incorporating recycled materials generally exhibits lower embodied carbon and reduced environmental impacts than conventional Portland cement concrete when appropriate material selection and quality control are adopted (Habert et al., 2020; World Green Building Council, 2023).

2.2.3 Low-Carbon Concrete Technologies

Reducing the carbon footprint of concrete has become an international priority because Portland cement production contributes approximately 7–8% of global anthropogenic CO_2 emissions. Consequently, numerous low-carbon concrete technologies have been developed to reduce cement consumption while maintaining engineering performance (Andrew, 2019).

Current low-carbon concrete technologies include:

- Partial replacement of Portland cement with Fly Ash, GGBS, Silica Fume, Calcined Clay, and Metakaolin.
- Utilization of Geopolymer Concrete (GPC) as a cement-free alternative.
- Incorporation of Recycled Concrete Aggregates (RCA).
- Carbon capture, utilization, and storage (CCUS).
- Limestone calcined clay cement (LC^3).
- Carbon mineralization technologies.
- Performance-based concrete mix design.
- Self-healing and durability-enhancing admixtures.

Among these technologies, the combined utilization of SCMs, RCA, and crystalline admixtures has demonstrated considerable potential for simultaneously improving durability and reducing embodied carbon emissions (Scrivener et al., 2018; Habert et al., 2020; GCCA, 2024).

Key Equation Representing the Relationship

Although there is no official engineering equation stating Durability = Sustainability, the relationship can be expressed conceptually as:

Higher Durability→ Longer Service Life→ Lower Life-Cycle Cost →Greater Sustainability

or

$$\textbf{Sustainability} \propto \textbf{Durability}$$

Meaning sustainability is directly proportional to durability, provided structural performance and functionality are maintained.

"Durability is the foundation of sustainable concrete. Increasing the durability of concrete through crystalline admixtures and geopolymer technology extends service life, reduces maintenance, conserves natural resources, lowers carbon emissions, and enhances the overall sustainability of infrastructure."

2.2.4 Alternative Cementitious Materials

Alternative cementitious materials are replacing a significant proportion of Portland cement in modern concrete technology. These materials include industrial by-products and naturally occurring pozzolans capable of participating in hydration or Geopolymerization reactions.

The most widely used alternative binders include:

- Fly Ash (FA)
- Ground Granulated Blast Furnace Slag (GGBS)
- Silica Fume (SF)
- Metakaolin (MK)
- Calcined Clay
- Rice Husk Ash (RHA)

These materials improve concrete performance through pozzolanic and latent hydraulic reactions that generate additional calcium silicate hydrate (C–S–H) and calcium aluminosilicate hydrate (C–A–S–H) gels. The resulting microstructural refinement reduces permeability, enhances durability, and improves long-term mechanical properties (Thomas, 2013; Lothenbach et al., 2011; Kumar et al., 2024).

2.2.5 Supplementary Cementitious Materials (SCMs)

Supplementary Cementitious Materials (SCMs) are finely divided mineral materials that react chemically with calcium hydroxide produced during cement hydration or exhibit latent hydraulic properties in alkaline environments. SCMs improve fresh and hardened concrete properties while reducing cement consumption and associated carbon emissions (Mehta & Monteiro, 2014).

The most commonly used SCMs include:

- Fly Ash
- GGBS
- Silica Fume
- Metakaolin
- Calcined Clay

Their incorporation provides several engineering advantages:

- Improved workability.
- Reduced heat of hydration.
- Increased later-age strength.
- Lower permeability.
- Improved chloride resistance.
- Enhanced sulfate resistance.
- Better carbonation resistance.
- Reduced alkali–silica reaction.
- Improved durability.
- Lower embodied carbon.

Recent investigations indicate that ternary SCM systems provide superior performance compared with binary binder systems owing to complementary hydration mechanisms and improved particle packing (Zhang et al., 2023; Li et al., 2024; Kumar et al., 2024).

Critical Analysis

The literature demonstrates that sustainable concrete technologies have evolved considerably during the past two decades. While the incorporation of SCMs, recycled aggregates, and geopolymer binders has significantly reduced environmental impacts, many published investigations have focused on these technologies independently. Comparatively fewer studies have evaluated their combined influence on durability, permeability reduction, and service-life enhancement. Furthermore, limited research has integrated SCMs with crystalline admixtures to investigate their synergistic effects on pore refinement, crack sealing, and sustainability under identical experimental conditions. This gap provides strong justification for the present research, which investigates the combined use of recycled aggregates, geopolymer binders, supplementary cementitious materials, and crystalline admixtures in developing durable and sustainable concrete systems (Habert et al., 2020; Zhao et al., 2024; UNEP, 2024).

2.2.6 Types of Supplementary Cementitious Materials (SCMs)

Supplementary Cementitious Materials (SCMs) are finely divided mineral materials that are incorporated into concrete either as partial replacements for Ordinary Portland Cement (OPC) or as additional cementitious constituents. SCMs improve the engineering performance of concrete through pozzolanic reactions, latent hydraulic reactions, and micro filler effects, resulting in enhanced strength, durability, and sustainability. Furthermore, SCMs reduce clinker consumption, lower greenhouse gas emissions, conserve natural resources, and promote the utilization of industrial by-products, thereby supporting sustainable construction and circular economy principles (Mehta & Monteiro, 2014; Thomas, 2013; Kumar et al., 2024).

The most commonly used SCMs include Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Silica Fume (SF), Metakaolin (MK), and Calcined Clay (CC). Each material possesses distinct chemical compositions and reactivity, contributing differently to concrete performance.

2.2.6.1 Fly Ash (FA)

Fly Ash is a finely divided by-product collected from coal-fired thermal power plants during coal combustion. It primarily consists of amorphous silica (SiO_2), alumina (Al_2O_3), and small quantities of iron oxide and calcium oxide. According to ASTM C618, fly ash is classified into Class F and Class C, depending on its calcium content. Class F fly ash is predominantly pozzolanic and is widely used in geopolymer concrete because of its high silica and alumina contents (ASTM C618, 2023).

When incorporated into concrete, fly ash reacts slowly with calcium hydroxide [$Ca(OH)_2$] released during cement hydration to produce additional calcium silicate hydrate (C–S–H) gel. This secondary hydration process refines the pore structure, reduces permeability, enhances workability, lowers the heat of hydration, and improves long-term compressive strength and durability. Fly ash also reduces chloride ion penetration, sulphate attack, and alkali–silica reaction (ASR), making it particularly suitable for mass concrete and marine structures (Thomas, 2013; Lothenbach et al., 2011; Zhang et al., 2023).

2.2.6.2 Ground Granulated Blast Furnace Slag (GGBS)

Ground Granulated Blast Furnace Slag (GGBS) is a latent hydraulic material obtained by rapidly quenching molten iron slag produced during iron manufacturing and subsequently grinding it into a fine powder. GGBS contains significant amounts of calcium oxide, silica, alumina, and magnesium oxide, enabling it to react under alkaline conditions to produce additional Calcium Silicate Hydrate (C–S–H) and Calcium Aluminosilicate Hydrate (C–A–S–H) gels (Shi et al., 2006).

The incorporation of GGBS significantly improves the microstructure of concrete by refining pore size distribution, reducing permeability, increasing sulphate resistance, minimizing chloride diffusion, and improving long-term mechanical performance. Owing to its latent hydraulic nature, GGBS also enhances early-age strength in geopolymer concrete when combined with fly ash, making it one of the most widely used SCMs in sustainable concrete technology (Provis & van Deventer, 2014; Kumar et al., 2024).

2.2.6.3 Silica Fume (SF)

Silica Fume, also known as Microsilica, is an ultrafine by-product generated during the production of silicon and ferrosilicon alloys. It consists of more than 90% amorphous silica with an average particle size approximately 100 times smaller than cement particles, making it one of the most reactive pozzolanic materials used in concrete (ACI 234R-06).

Silica fume enhances concrete performance through two complementary mechanisms:

1. **Micro filler Effect** – Ultrafine particles fill microscopic voids between cement grains, improving particle packing and reducing capillary porosity.
2. **Pozzolanic Reaction** – Silica reacts rapidly with calcium hydroxide to generate additional C–S–H gel, producing a denser cement matrix.

These mechanisms substantially improve compressive strength, flexural strength, chloride resistance, abrasion resistance, and the durability of concrete. Silica fume also produces a dense Interfacial Transition Zone (ITZ) between aggregate particles and cement paste, reducing micro cracking and improving long-term durability (Mehta & Monteiro, 2014; Zhang et al., 2023).

2.2.6.4 Metakaolin (MK)

Metakaolin is a highly reactive pozzolanic material produced by calcining purified kaolinite clay at temperatures ranging from 650°C to 800°C. Unlike industrial by-products such as fly ash and GGBS, metakaolin is manufactured specifically as a supplementary cementitious material. It possesses high alumina and silica contents, enabling rapid pozzolanic reactions with calcium hydroxide.

Concrete incorporating metakaolin exhibits higher early-age strength, lower permeability, improved sulfate resistance, enhanced chloride resistance, and refined pore structure. The incorporation of metakaolin also improves the interfacial transition zone and reduces efflorescence, making it suitable for high-performance and durable concrete applications (Sabir et al., 2001; Siddique & Klaus, 2009).

2.2.6.5 Calcined Clay (CC)

Calcined clay has recently emerged as one of the most promising low-carbon supplementary cementitious materials because of its widespread availability and relatively low processing energy requirements. Calcination activates clay minerals, producing reactive aluminosilicate phases capable of participating in pozzolanic reactions.

The combination of Calcined Clay and Limestone (LC^3 technology) has demonstrated substantial reductions in Portland cement consumption while maintaining satisfactory mechanical properties and durability. Recent studies indicate that LC^3 systems can reduce carbon emissions by approximately 30–40% compared with conventional Portland cement concrete while improving resistance to chloride penetration and sulphate attack (Scrivener et al., 2018; Kumar et al., 2024).

Table 2.2 Types of Supplementary Cementitious Materials

SCM	Source	Primary Reaction	Major Benefits
Fly Ash	Thermal power plants	Pozzolanic	Improved workability, reduced permeability, higher durability
GGBS	Iron and steel industry	Latent hydraulic	Higher strength, sulphate resistance, chloride resistance
Silica Fume	Silicon alloy industry	Highly pozzolanic	Dense ITZ, high strength, low permeability
Metakaolin	Calcined kaolinite clay	Pozzolanic	Early strength, refined pore structure
Calcined Clay	Calcined natural clay	Pozzolanic	Lower CO_2 emissions, improved durability

Source: Adapted from Mehta and Monteiro (2014), Thomas (2013), Scrivener et al. (2018), and Kumar et al. (2024).

Critical Analysis

Although Fly Ash, GGBS, Silica Fume, Metakaolin, and Calcined Clay have each demonstrated significant improvements in concrete performance, the majority of previous investigations have focused on individual SCMs or binary blend systems. Recent research suggests that ternary blend systems, particularly those combining Fly Ash, GGBS, and Silica Fume, provide superior mechanical performance, enhanced pore refinement, lower permeability, and improved long-term durability due to complementary hydration and particle-packing mechanisms (Zhang et al., 2023; Li et al., 2024). However, limited studies have investigated the combined use of ternary SCM systems with crystalline admixtures in recycled aggregate and geopolymer concrete under identical experimental conditions. This research gap forms an important basis for the present study.

2.2.7 Mechanism of Microstructural Enhancement by Supplementary Cementitious Materials

The incorporation of Supplementary Cementitious Materials (SCMs) significantly enhances the microstructure of concrete through a combination of pozzolanic reactions, latent hydraulic reactions, and microfiller effects. These mechanisms collectively reduce pore connectivity, improve the Interfacial Transition Zone (ITZ), increase matrix density, and enhance the mechanical and durability performance of concrete. The resulting refinement of the cementitious matrix reduces the ingress of water and aggressive ions, thereby extending the service life of concrete structures (Lothenbach et al., 2011; Thomas, 2013; Mehta & Monteiro, 2014).

2.2.7.1 Stage 1: Pozzolanic and Hydraulic Reactions

During cement hydration, Ordinary Portland Cement reacts with water to produce Calcium Silicate Hydrate (C–S–H) gel and Calcium Hydroxide (CH). While C–S–H contributes significantly to strength development, calcium hydroxide is relatively weak and susceptible to chemical attack. SCMs utilize this calcium hydroxide through pozzolanic reactions, converting it into additional cementitious hydration products.

Fly Ash, Silica Fume, Metakaolin, and Calcined Clay react with calcium hydroxide according to the generalized pozzolanic reaction:

$$Ca(OH)2+SiO2+H2O \rightarrow C-S-H$$

Similarly, GGBS undergoes latent hydraulic reactions under alkaline conditions to produce additional C–S–H and Calcium Aluminosilicate Hydrate (C–A–S–H) gels. These reactions consume undesirable calcium hydroxide and generate stronger hydration products that enhance concrete performance (Lothenbach et al., 2011; Provis & van Deventer, 2014).

2.2.7.2 Stage 2: Formation of Additional Hydration Products

The secondary hydration reactions produce additional C–S–H and C–A–S–H gels that progressively fill capillary pores and internal voids within the cement matrix. These newly formed hydration products improve particle bonding, reduce pore continuity, and increase matrix density. As hydration continues, the cement paste becomes progressively more homogeneous, resulting in improved compressive strength and reduced permeability (Thomas, 2013; Kumar et al., 2024).

The increased formation of secondary hydration products also contributes to improved long-term strength development, particularly in concrete containing Fly Ash and GGBS. Although early-age strength may be slightly lower for some SCM systems, continued hydration produces significant strength gains at later ages (Mehta & Monteiro, 2014).

2.2.7.3 Stage 3: Pore Structure Refinement

One of the most important contributions of SCMs is the refinement of the pore structure. The additional hydration products generated through pozzolanic and hydraulic reactions fill interconnected capillary pores, reducing both pore size and pore connectivity. Simultaneously, the micro filler effect of ultrafine SCM particles improves particle packing by occupying spaces between cement grains.

The resulting dense microstructure substantially decreases water permeability, chloride diffusion, sulphate ingress, and carbonation depth. Numerous studies have demonstrated that concrete incorporating SCMs exhibits significantly lower permeability than conventional Portland cement concrete, resulting in enhanced durability under aggressive environmental conditions (Zhang et al., 2023; Li et al., 2024).

2.2.7.4 Stage 4: Densification of the Interfacial Transition Zone (ITZ)

The Interfacial Transition Zone (ITZ) surrounding coarse aggregate particles is generally considered the weakest region within concrete because of its relatively high porosity and concentration of microcracks. The incorporation of SCMs substantially improves the quality of the ITZ through additional hydration and pore refinement.

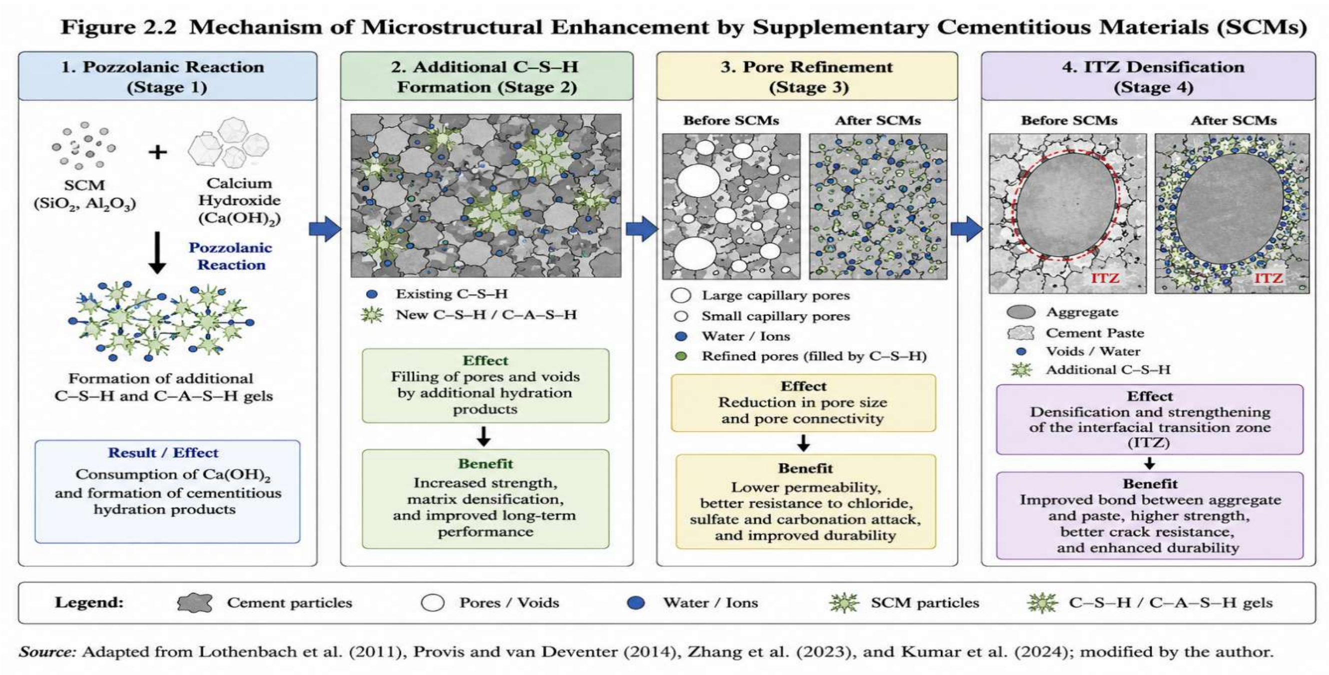
Ultrafine particles such as Silica Fume effectively fill microscopic voids adjacent to aggregate surfaces, while secondary C–S–H and C–A–S–H gels strengthen the aggregate–paste interface. Consequently, the ITZ becomes denser and more homogeneous, reducing stress concentrations, limiting crack propagation, and improving the bond between aggregates and the surrounding cement matrix. This enhancement contributes directly to increased compressive strength, tensile strength, and long-term durability (Mehta & Monteiro, 2014; Thomas, 2013; Kumar et al., 2024).

Table 2.3 Mechanism of Microstructural Enhancement by SCMs

Stage	Mechanism	Microstructural Effect	Engineering Benefit
Stage 1	Pozzolanic and hydraulic reactions	Consumption of calcium hydroxide	Additional C–S–H and C–A–S–H formation
Stage 2	Secondary hydration	Formation of additional hydration products	Increased strength and matrix densification
Stage 3	Pore refinement	Reduction in capillary pore size and connectivity	Lower permeability and improved durability
Stage 4	ITZ densification	Stronger aggregate–paste interface	Higher mechanical strength and crack resistance

Source: Adapted from Lothenbach et al. (2011), Mehta and Monteiro (2014), Thomas (2013), Provis and van Deventer (2014), Zhang et al. (2023), and Kumar et al. (2024).

Figure 2.2Mechanism of Microstructural Enhancement by Supplementary Cementitious Materials



1. Pozzolanic Reaction
2. Additional C–S–H Formation
3. Pore Refinement
4. ITZ Densification

Source: Adapted from Lothenbach et al. (2011), Provis and van Deventer (2014), Zhang et al. (2023), and Kumar et al. (2024); modified by the author.

Critical Analysis

The literature consistently demonstrates that the effectiveness of SCMs depends not only on their chemical composition but also on their particle size, replacement level, curing conditions, and interaction with other constituents of the concrete matrix. While individual SCMs improve concrete performance through distinct mechanisms, recent research indicates that ternary blend systems combining Fly Ash, GGBS, and Silica Fume provide superior pore refinement, enhanced ITZ quality, and improved durability compared with single or binary SCM systems (Zhang et al., 2023; Li et al., 2024). However, there remains limited research on how these microstructural improvements interact with crystalline admixtures to further enhance permeability resistance and long-term durability, particularly in Recycled Aggregate Concrete (RAC) and Geopolymer Concrete (GPC). This research gap provides a strong justification for the present study.

2.2.8 Effect of Supplementary Cementitious Materials on Pore Structure and Interfacial Transition Zone (ITZ)

The incorporation of Supplementary Cementitious Materials (SCMs) significantly modifies the pore structure and improves the quality of the Interfacial Transition Zone (ITZ), which are two of the most influential microstructural parameters governing the mechanical properties and durability of concrete. Through pozzolanic reactions, latent hydraulic reactions, and the micro filler effect, SCMs reduce pore connectivity, decrease porosity, and strengthen the bond between aggregates and the surrounding cement paste. These microstructural improvements substantially reduce permeability, increase strength, and enhance long-term durability (Mehta & Monteiro, 2014; Lothenbach et al., 2011; Thomas, 2013).

The pore structure of conventional Portland cement concrete is generally characterized by interconnected capillary pores, entrapped air voids, and microcracks that provide pathways for the ingress of water, chlorides, sulphate's, and carbon dioxide. These interconnected pores significantly influence permeability and the deterioration of reinforced concrete structures. The incorporation of SCMs promotes the formation of additional hydration products that progressively fill these capillary pores, resulting in a denser and more homogeneous cementitious matrix (Scrivener et al., 2018; Zhang et al., 2023).

Fly Ash contributes to pore refinement through its pozzolanic reaction with calcium hydroxide, producing secondary C–S–H gel that gradually fills internal voids and reduces capillary pore size. Although strength development is relatively slower during the early curing period, continuous hydration significantly improves the pore structure at later ages, leading to reduced permeability and enhanced durability (Thomas, 2013; Kumar et al., 2024).

Ground Granulated Blast Furnace Slag (GGBS) exhibits latent hydraulic behaviour and forms additional C–S–H and C–A–S–H gels under alkaline conditions. These hydration products produce a refined pore network with reduced pore connectivity and improved resistance to chloride penetration and sulphate attack. The dense microstructure produced by GGBS also enhances later-age compressive strength and decreases water absorption (Provis & van Deventer, 2014; Shi et al., 2006).

Silica Fume provides the greatest degree of pore refinement among commonly used SCMs because of its extremely fine particle size and exceptionally high pozzolanic activity. The ultrafine particles occupy microscopic voids between cement grains while simultaneously reacting with calcium hydroxide to generate additional C–S–H gel. Consequently, concrete containing Silica Fume exhibits very low porosity, high matrix density, excellent chloride resistance, and superior mechanical performance (ACI Committee 234, 2006; Mehta & Monteiro, 2014).

The Interfacial Transition Zone (ITZ) is widely recognized as the weakest region within concrete because it contains larger crystals of calcium hydroxide, higher porosity, and greater concentrations of microcracks than the bulk cement paste. The addition of SCMs significantly improves the ITZ by reducing calcium hydroxide content, refining pore structure, and producing additional hydration products that strengthen the aggregate–paste interface. A denser ITZ minimizes stress concentrations, delays crack initiation, and enhances both compressive and tensile strength (Scrivener et al., 2018; Thomas, 2013).

Numerous microstructural investigations using Scanning Electron Microscopy (SEM), Mercury Intrusion Porosimetry (MIP), and X-ray Diffraction (XRD) have confirmed that SCM-modified concrete contains fewer large capillary pores, reduced micro cracking, improved particle packing, and a more continuous cementitious matrix compared with conventional Portland cement concrete. These improvements directly contribute to lower permeability, higher durability, and extended service life under aggressive environmental conditions (Lothenbach et al., 2011; Zhang et al., 2023).

Table 2.4 Effect of SCMs on Pore Structure and ITZ

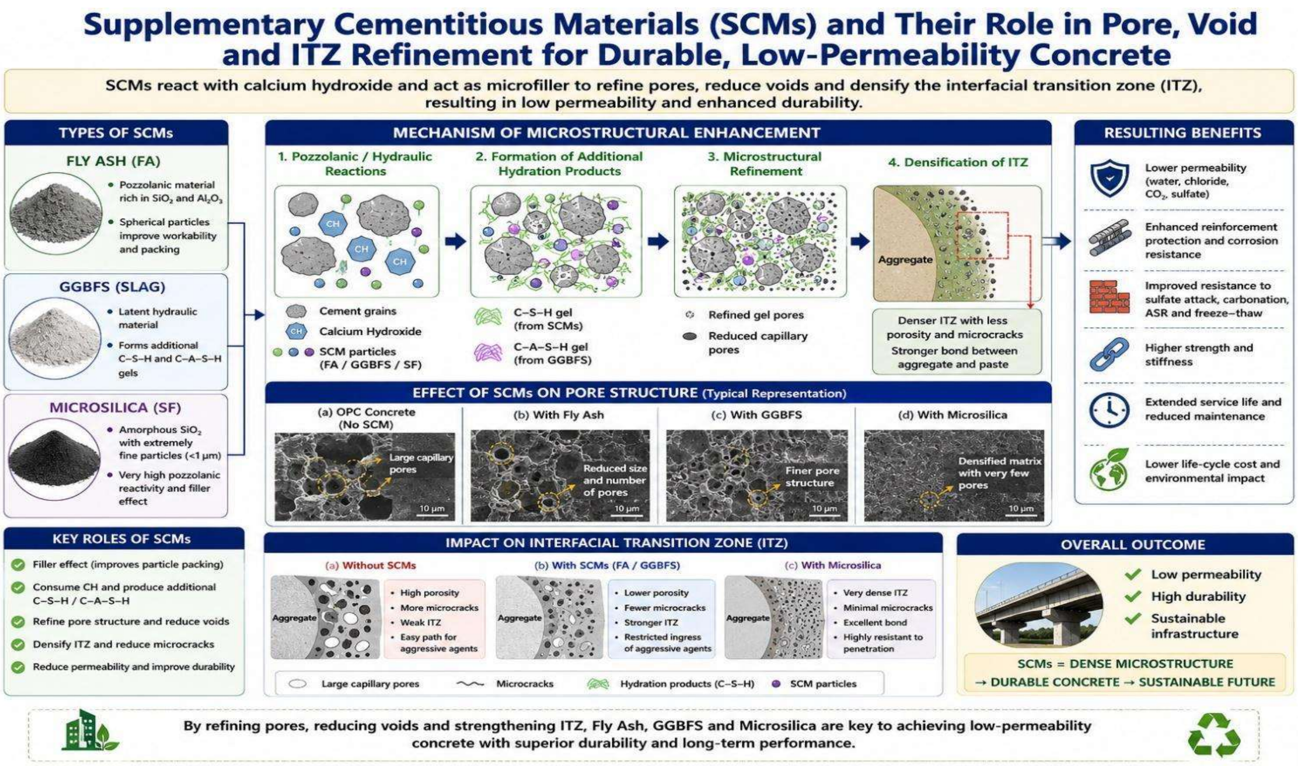
SCM	Effect on Pore Structure	Effect on ITZ	Overall Engineering Benefit
Fly Ash	Reduces capillary pore size through secondary C–S–H formation	Improves aggregate–paste bond	Lower permeability and improved long-term durability

GGBS	Produces dense C–S–H and C–A–S–H gel network	Refines ITZ and reduces porosity	Increased strength and sulfate resistance
Silica Fume	Provides maximum pore refinement through microfiller effect	Produces very dense ITZ with minimal micro cracking	Superior strength, chloride resistance, and durability
Metakaolin	Refines pore distribution through rapid pozzolanic reactions	Strengthens ITZ and reduces CH crystals	High early strength and durability
Calcined Clay	Produces additional hydration products and finer pore network	Improves matrix uniformity	Lower CO_2 emissions and enhanced long-term performance

Source: Adapted from Mehta and Monteiro (2014), Thomas (2013), Lothenbach et al. (2011), Provis and van Deventer (2014), Zhang et al. (2023), and Kumar et al. (2024).

Figure 2.3 :Effect of Supplementary Cementitious Materials on Pore Structure and Interfacial Transition Zone (ITZ)

Figure 2.3. Schematic illustration showing the influence of Supplementary Cementitious Materials on pore refinement and densification of the Interfacial Transition Zone (ITZ). Additional C–S–H and C–A–S–H gels formed through pozzolanic and latent hydraulic reactions reduce capillary porosity, strengthen the aggregate–paste interface, and improve durability.



Source: Adapted from Lothenbach et al. (2011), Thomas (2013), Mehta and Monteiro (2014), Zhang et al. (2023), and modified by the author.

Critical Analysis

The available literature consistently demonstrates that SCMs significantly improve the microstructure of concrete by refining pore size distribution, reducing capillary porosity, and strengthening the ITZ. While Fly Ash, GGBS, and Silica Fume each provide distinct benefits, recent studies indicate that ternary SCM systems achieve greater pore refinement and durability than individual SCMs because of their complementary hydration mechanisms. Nevertheless, limited research has explored how these refined microstructures interact with crystalline admixtures to further reduce permeability and promote self-sealing in Recycled Aggregate Concrete (RAC) and Geopolymer Concrete (GPC). Addressing this knowledge gap forms an important objective of the present investigation (Zhang et al., 2023; Kumar et al., 2024; Zhao et al., 2024).

2.2.9 Key Roles of Supplementary Cementitious Materials (SCMs) in Sustainable Concrete

Supplementary Cementitious Materials (SCMs) have become essential constituents of modern sustainable concrete because they simultaneously improve the engineering performance, durability, and environmental sustainability of cement-based materials. Their effectiveness is attributed to three primary mechanisms: the pozzolanic reaction, the latent hydraulic reaction, and the micro filler effect. These mechanisms modify the microstructure of concrete by generating additional hydration products, refining the pore network, strengthening the Interfacial Transition Zone (ITZ), and reducing permeability. Consequently, SCMs significantly improve both the short-term and long-term performance of concrete structures (Mehta & Monteiro, 2014; Thomas, 2013; Lothenbach et al., 2011).

2.2.9.1 Micro filler Effect

One of the primary functions of SCMs is the microfiller effect. The extremely fine particles of materials such as Silica Fume and Fly Ash occupy the spaces between cement grains, reducing internal voids and improving particle packing density. This refined particle arrangement decreases capillary porosity, increases matrix compactness, and enhances the overall homogeneity of the cement paste. Improved particle packing also reduces bleeding and segregation while enhancing workability in fresh concrete (Mehta & Monteiro, 2014; ACI Committee 234, 2006).

2.2.9.2 Consumption of Calcium Hydroxide

During the hydration of Ordinary Portland Cement, significant quantities of calcium hydroxide (CH) are produced. Although CH is a normal hydration product, it contributes little to strength development and is susceptible to chemical attack. SCMs consume calcium hydroxide through pozzolanic reactions, producing additional calcium silicate hydrate (C–S–H) gel, which is the primary strength-giving phase in concrete. This process reduces the amount of weak CH crystals while increasing the volume of durable hydration products, thereby improving both strength and durability (Lothenbach et al., 2011; Thomas, 2013).

2.2.9.3 Formation of Additional Cementitious Gels

Fly Ash, GGBS, Silica Fume, and other SCMs generate secondary hydration products such as **C–S–H** and **Calcium Aluminosilicate Hydrate (C–A–S–H)** gels. These additional hydration products fill capillary pores, strengthen the cement matrix, and improve the bond between aggregate and paste. The formation of secondary gels also contributes to increased later-age strength and significantly reduces the permeability of concrete (Provis & van Deventer, 2014; Kumar et al., 2024).

2.2.9.4 Refinement of Pore Structure

SCMs play a vital role in refining the pore structure of concrete by reducing pore size, decreasing pore connectivity, and minimizing internal discontinuities. The resulting dense microstructure restricts the movement of water, chlorides, sulfates, carbon dioxide, and other aggressive agents. Consequently, concrete containing SCMs exhibits significantly lower water absorption, reduced chloride permeability, and improved resistance to aggressive environmental exposure compared with conventional Portland cement concrete (Zhang et al., 2023; Li et al., 2024).

2.2.9.5 Densification of the Interfacial Transition Zone (ITZ)

The Interfacial Transition Zone (ITZ) surrounding coarse aggregate particles is generally the weakest region of concrete due to its relatively high porosity and microcrack density. SCMs improve the ITZ by producing additional hydration products and reducing calcium hydroxide accumulation adjacent to aggregate surfaces. The resulting dense ITZ improves aggregate–paste bonding, delays crack propagation, and enhances both compressive and tensile strength (Scrivener et al., 2018; Mehta & Monteiro, 2014).

2.2.9.6 Reduction in Permeability

Concrete durability is strongly influenced by its permeability. SCMs reduce permeability by refining the pore network and interrupting continuous capillary pathways. Lower permeability significantly reduces the ingress of chlorides, sulfates, carbon dioxide, and moisture, thereby delaying reinforcement corrosion and other deterioration mechanisms. Numerous studies have confirmed that concrete incorporating SCMs exhibits substantially lower Rapid Chloride Permeability Test (RCPT) values and improved long-term durability (Thomas, 2013; Kumar et al., 2024).

2.2.9.7 Improvement in Mechanical Properties

The formation of additional hydration products and the refinement of the microstructure contribute directly to improvements in mechanical performance. Concrete containing SCMs generally exhibits increased compressive strength, improved split tensile strength, higher flexural strength, and greater stiffness, particularly at later ages. Ternary binder systems combining Fly Ash, GGBS, and Silica Fume have demonstrated superior strength development due to their complementary hydration mechanisms (Li et al., 2024; Zhang et al., 2023).

2.2.9.8 Enhancement of Durability

The improved microstructure produced by SCMs significantly enhances resistance to deterioration mechanisms such as chloride ingress, sulphate attack, carbonation, alkali–silica reaction (ASR), freeze–thaw damage, and chemical attack. These improvements contribute to longer service life, reduced maintenance requirements, and lower life-cycle costs (Neville, 2011; Thomas, 2013; Kumar et al., 2024).

2.2.9.9 Contribution to Sustainability

In addition to improving engineering performance, SCMs contribute substantially to sustainable construction by reducing Portland cement consumption, lowering embodied carbon emissions, utilizing industrial by-products, conserving natural resources, and promoting circular economy principles. These environmental benefits support the global transition toward low-carbon and resource-efficient infrastructure while contributing directly to the United Nations Sustainable Development Goals (SDGs) and Net Zero initiatives (Habert et al., 2020; UNEP, 2024).

Table 2.5 Key Roles of Supplementary Cementitious Materials

Role of SCMs	Microstructural Effect	Engineering Benefit
Micro filler Effect	Improved particle packing	Reduced porosity and bleeding
Pozzolanic Reaction	Consumption of CH	Additional C–S–H formation
Latent Hydraulic Reaction	Formation of C–A–S–H gel	Increased later-age strength
Pore Refinement	Reduced pore size and connectivity	Lower permeability
ITZ Densification	Stronger aggregate–paste interface	Improved mechanical performance
Durability Enhancement	Reduced ingress of aggressive agents	Extended service life
Sustainability	Reduced cement consumption	Lower embodied CO_2 emissions

Source: Adapted from Mehta and Monteiro (2014), Thomas (2013), Lothenbach et al. (2011), Habert et al. (2020), Zhang et al. (2023), Kumar et al. (2024), and modified by the author.

Critical Analysis

The literature consistently demonstrates that SCMs play multiple roles in improving concrete performance beyond simple cement replacement. Their ability to refine pore structure, strengthen the ITZ, generate additional hydration products, and reduce permeability makes them essential for producing durable and sustainable concrete. Recent studies indicate that ternary SCM systems provide greater improvements than individual SCMs because of synergistic hydration mechanisms. However, limited information is available regarding the combined interaction of SCMs, Recycled Concrete Aggregates (RCA), Geopolymer Concrete (GPC), and Crystalline Admixtures (CA). This gap forms the basis of the present research, which evaluates these technologies together to develop high-performance, low-permeability, and environmentally sustainable concrete.

2.3 Recycled Aggregate Concrete (RAC)

2.3 Recycled Aggregate Concrete (RAC): Current Developments, Challenges and Future Perspectives

The rapid growth of urbanization and infrastructure development has led to a substantial increase in construction and demolition waste (CDW) worldwide. The construction sector consumes nearly 40–50% of extracted natural resources and generates one of the largest waste streams globally. Disposal of demolished concrete in landfills occupies valuable land, contributes to environmental pollution, and accelerates the depletion of natural aggregate resources. Consequently, recycling concrete waste into Recycled Concrete Aggregate (RCA) has emerged as an effective strategy to support sustainable construction, conserve natural resources, and promote a circular economy (Silva et al., 2014; Xiao et al., 2012; UNEP, 2024).

Recycled Aggregate Concrete (RAC) is produced by partially or completely replacing natural coarse aggregates with recycled concrete aggregates obtained from demolished buildings, pavements, bridges, and other concrete structures. Unlike natural aggregates, RCA particles contain adhered cement mortar, which increases porosity, water absorption, and micro cracking. These characteristics influence fresh and hardened concrete properties, particularly workability, strength, permeability, and long-term durability. Nevertheless, advances in aggregate processing, supplementary cementitious materials (SCMs), chemical admixtures, and optimized mix design have significantly improved RAC performance, making it suitable for structural applications (Guo et al., 2018; Zhao et al., 2021; Luo et al., 2022).

Internationally, many developed countries such as Japan, Germany, the Netherlands, Singapore, and Australia have adopted national policies encouraging the use of recycled aggregates in construction. In India, increasing infrastructure development and the implementation of Construction and Demolition Waste Management Rules have accelerated research on RCA utilization in structural concrete. These initiatives align with the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production), highlighting RAC as an important component of sustainable infrastructure development.

Figure 2.2 Circular Economy Concept of Recycled Aggregate Concrete

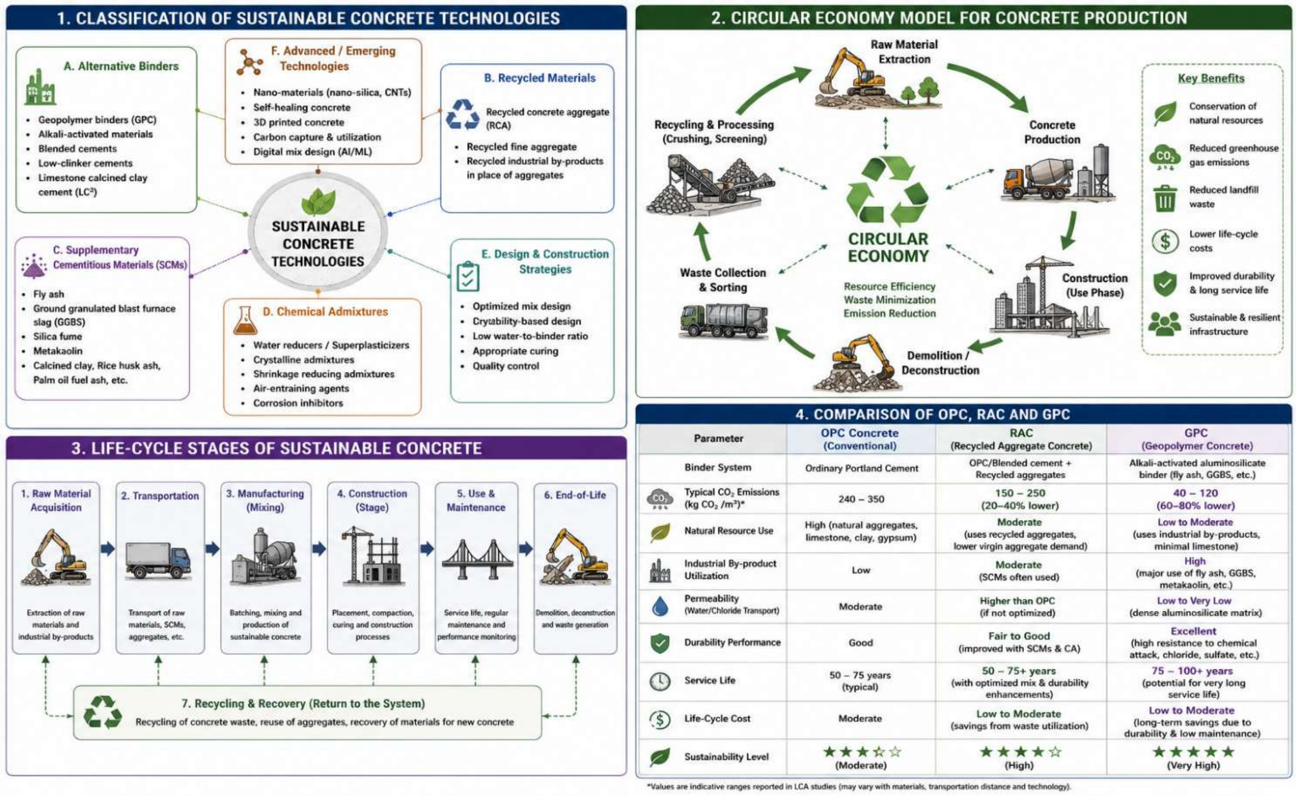


Figure 2.2. Circular economy framework illustrating the recycling of construction and demolition waste into recycled aggregate concrete. Source: Adapted from Silva et al. (2014); UNEP (2024).

2.3.1 Production of Recycled Concrete Aggregate

The production of RCA involves a systematic sequence of demolition, crushing, screening, removal of contaminants, grading, and quality control. Initially, demolished concrete is collected from buildings, bridges, pavements, and other reinforced concrete structures. Steel reinforcement and other contaminants such as wood, plastics, bricks, and asphalt are removed using magnetic separators and manual sorting. The concrete is then crushed using primary and secondary crushers, followed by screening into different aggregate sizes suitable for concrete production.

Compared with natural aggregates, RCA possesses residual cement paste attached to the aggregate surface. This adhered mortar is responsible for increased porosity, lower density, higher water absorption, and a weaker interfacial transition zone (ITZ). Modern processing methods such as mechanical grinding, carbonation treatment, thermal treatment, and acid treatment have been proposed to reduce adhered mortar and improve RCA quality. Recent studies demonstrate that these treatment techniques significantly improve aggregate density, reduce water absorption, and enhance the mechanical and durability performance of RAC (Guo et al., 2018; Wang et al., 2021).

Figure 2.3. Typical production process of recycled concrete aggregate from construction and demolition waste.

Source: Adapted from Xiao et al. (2012); Guo et al. (2018).

Table 2.2: Physical Properties of Natural Coarse Aggregate and Recycled Concrete Aggregate

Property	Natural Coarse Aggregate (NCA)	Recycled Concrete Aggregate (RCA)	Engineering Implication
Specific Gravity	2.60–2.75	2.30–2.60	Lower concrete density
Water Absorption (%)	0.5–2.0	3.0–8.0	Higher water demand
Bulk Density (kg/m³)	1500–1700	1250–1450	Reduced unit weight
Porosity	Low	High	Increased permeability
Adhered Mortar	Absent	Present	Weaker ITZ
Crushing Resistance	Higher	Moderate	Slight reduction in strength
Surface Texture	Smooth	Rough	Better mechanical interlock

Source: Compiled by the Author based on Silva et al. (2014); Guo et al. (2018); Wang et al. (2021).

Table 2.3 Advantages and Limitations of Recycled Aggregate Concrete

Advantages	Limitations
Conserves natural aggregates	Higher water absorption

Reduces construction and demolition waste	Presence of adhered mortar
Supports circular economy	Increased porosity
Lowers environmental impact	Reduced workability
Reduces landfill disposal	Variable aggregate quality
Suitable for structural concrete with optimized mix design	Higher permeability at high RCA replacement
Decreases demand for quarrying	Additional processing may be required

Source: Compiled by the Author based on Silva et al. (2014); Zhao et al. (2021); Luo et al. (2022); UNEP (2024).

Summary

The literature confirms that recycled aggregate concrete provides a sustainable alternative to conventional concrete by utilizing construction and demolition waste while conserving natural resources. Although RCA exhibits higher porosity and water absorption due to adhered mortar, advances in processing technologies and mix optimization have significantly improved its engineering performance. These developments have positioned RAC as a viable material for structural applications and an important contributor to circular economy principles and sustainable infrastructure development.

2.3.3 Sustainability, Recent Developments and Future Perspectives of Recycled Aggregate Concrete

Sustainability has become one of the principal drivers behind the increasing adoption of Recycled Aggregate Concrete (RAC). The construction industry is responsible for significant consumption of natural resources, accounting for approximately 40% of global raw material extraction and generating nearly one-third of the world's solid waste. Construction and demolition waste (CDW) constitutes the largest portion of this waste stream, with millions of tonnes produced annually due to infrastructure replacement, urban redevelopment, and natural disasters. Recycling demolished concrete into recycled concrete aggregates (RCA) addresses two major environmental concerns simultaneously: reducing landfill disposal and conserving diminishing natural aggregate resources. Consequently, RAC has become an essential component of circular economy strategies aimed at minimizing waste generation while promoting sustainable infrastructure development (Silva et al., 2014; UNEP, 2024).

The environmental benefits of RAC extend beyond waste utilization. Every cubic metre of concrete produced using recycled aggregates reduces the extraction of virgin stone from quarries, decreases transportation requirements, and minimizes ecosystem degradation associated with aggregate mining. Moreover, when RAC is combined with supplementary cementitious materials (SCMs) such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), and silica fume, both clinker consumption and greenhouse gas emissions are substantially reduced. Recent life-cycle assessment (LCA) studies indicate that the environmental performance of RAC improves significantly when durability is simultaneously enhanced, since extending service life reduces future repair, maintenance, and reconstruction activities. Therefore, durability and sustainability should be evaluated as complementary rather than independent performance criteria.

Recent research has shifted from simply replacing natural aggregates toward developing high-performance recycled aggregate concrete capable of satisfying structural, durability, and sustainability requirements simultaneously. Advanced treatment methods such as accelerated carbonation, mechanical abrasion, microbial treatment, acid soaking, and Nano-material modification have been developed to improve RCA quality by removing or densifying adhered mortar. These techniques reduce porosity, strengthen the interfacial transition zone (ITZ), decrease water absorption, and improve resistance against chloride penetration and carbonation. Among these methods, accelerated carbonation has attracted considerable attention because it simultaneously improves RCA quality while permanently sequestering carbon dioxide within the adhered mortar. Recent experimental studies demonstrate that carbonation-treated RCA exhibits significantly improved mechanical and durability performance compared with untreated aggregates.

The integration of crystalline admixtures represents another promising development in sustainable RAC technology. Crystalline admixtures react with moisture and unhydrated cement particles to form insoluble crystalline products that fill capillary pores and microcracks, thereby reducing permeability and improving long-term durability. Although these admixtures have been extensively investigated in conventional Portland cement concrete, comparatively limited research has evaluated their effectiveness in recycled aggregate concrete. Existing studies suggest that crystalline admixtures can partially compensate for the higher permeability associated with RCA by refining pore connectivity and reducing chloride ingress. However, systematic investigations evaluating optimum crystalline admixture dosages in medium-strength RAC remain scarce, particularly for replacement levels around 60% RCA, which forms the basis of the present investigation.

2.3.3.a Sustainable Development Framework of Recycled Aggregate Concrete (RAC)

The Sustainable Development Framework of Recycled Aggregate Concrete (RAC) integrates the three pillars of sustainability—environmental, economic, and social—with the technical performance of recycled aggregate concrete. The framework demonstrates how replacing natural coarse aggregates with recycled concrete aggregates (RCA), together with durability enhancement measures such as supplementary cementitious materials (SCMs) and crystalline admixtures, contributes to long-term sustainable infrastructure.

Sustainable Development Framework

Construction & Demolition Waste (CDW)

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▼

Collection and Processing of Waste

▼

Production of Recycled Aggregate (RCA)

▼

Mix Design Optimization (RCA + SCM + CA)

▼

Improved Fresh and Hardened Properties

▼

Enhanced Durability Performance

(Reduced Permeability, Crack Control, Corrosion Resistance)

▼

Extended Service Life of Structures

▼

Sustainable Development Outcomes

- **Environmental Sustainability**
  - Reduced landfill disposal
  - Conservation of natural aggregates
  - Lower CO_2 emissions
  - Reduced embodied energy
  - Circular economy

+

- **Economic Sustainability**
  - Lower material cost
  - Reduced maintenance expenditure
  - Lower life-cycle cost
  - Improved resource efficiency

+

- **Social Sustainability**
  - Sustainable infrastructure
  - Improved public safety
  - Job creation in recycling industry
  - Better quality of life

|

▼

Sustainable and Resilient Infrastructure

Components of the Framework

Framework Component	Sustainability Contribution
Construction and Demolition Waste Recycling	Reduces landfill disposal and environmental pollution
Recycled Aggregate Production	Conserves natural stone resources
SCMs (Fly Ash, GGBS, Silica Fume)	Lowers cement consumption and CO_2 emissions
Crystalline Admixtures	Improves durability through pore refinement and self-sealing
Optimized Mix Design	Balances strength, durability, and sustainability
Durability Enhancement	Extends service life and reduces maintenance
Life-Cycle Assessment (LCA)	Quantifies environmental impacts over the structure's life
Circular Economy	Encourages reuse of construction materials and waste minimization

Sustainability Indicators

Environmental	Economic	Social
CO_2 reduction	Lower initial material cost	Improved infrastructure reliability
Reduced landfill waste	Reduced maintenance cost	Better public safety
Conservation of natural aggregates	Longer service life	Employment in recycling sector
Lower embodied energy	Improved life-cycle cost	Sustainable urban development
Resource efficiency	Better return on investment	Improved quality of life

Relationship Between Durability and Sustainability

Recycled Aggregate

|

▼

Optimized Mix Design

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▼

Enhanced Durability

|

▼

Longer Service Life

|

▼

Reduced Maintenance

|

▼

Lower Life-Cycle Cost

|

▼

Reduced Carbon Footprint

|

▼

SUSTAINABLE DEVELOPMENT

Key Benefits

- Promotes the circular economy through the reuse of construction and demolition waste.
- Conserves natural aggregate resources and reduces quarrying.
- Minimizes landfill disposal and associated environmental impacts.
- Lowers embodied carbon by incorporating recycled materials and SCMs.
- Enhances durability, reducing repair frequency and extending service life.
- Reduces life-cycle costs through lower maintenance and replacement needs.
- Supports resilient, resource-efficient, and sustainable infrastructure.

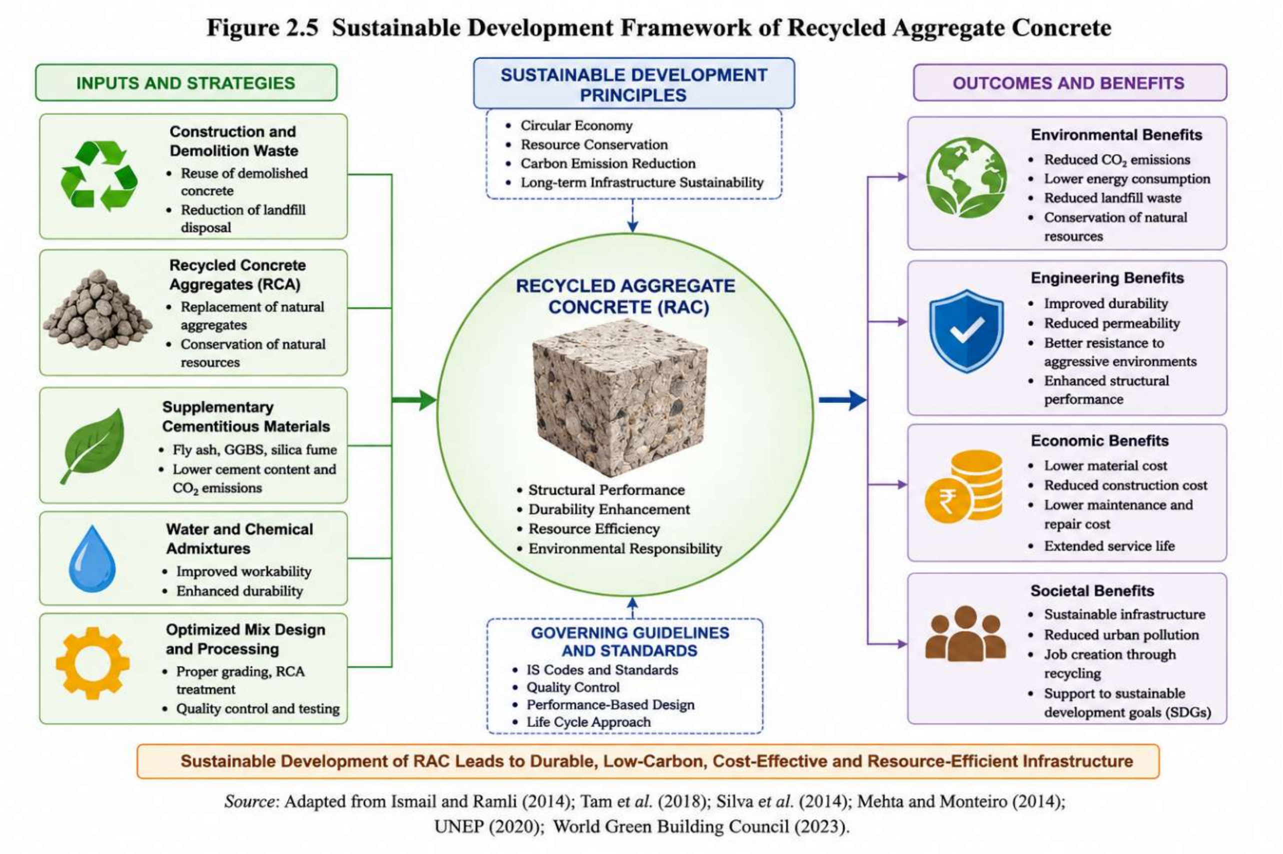
Integrated Sustainable Development Framework for RAC

Construction & Demolition Waste → Recycled Aggregate → Optimized RAC Mix (SCMs + Crystalline Admixture) → Improved Mechanical Performance → Enhanced Durability → Extended Service Life → Reduced Maintenance → Lower Life-Cycle Cost + Reduced CO_2 Emissions + Resource Conservation + Circular Economy → Sustainable Infrastructure

This integrated framework aligns with the principles of sustainable construction and demonstrates that durability enhancement is the primary pathway through which Recycled Aggregate Concrete achieves long-term sustainability.

Figure 2.5 Sustainable Development Framework of Recycled Aggregate Concrete

Figure 2.5. Sustainability framework illustrating the environmental benefits of recycled aggregate concrete through resource conservation, waste reduction, durability enhancement, and life-cycle performance.



Source: Adapted from Silva et al. (2014); UNEP (2024); Akbulut et al. (2025).

Table 2.6 Sustainability Benefits of Recycled Aggregate Concrete

Sustainability Indicator	Contribution of RAC	Engineering Benefit
Construction waste recycling	Utilizes CDW	Reduces landfill disposal
Natural aggregate conservation	Reduces quarrying	Conserves natural resources
Reduced transportation	Local recycling	Lower fuel consumption
Reduced embodied energy	Less virgin aggregate production	Lower environmental impact
Circular economy	Material reuse	Sustainable construction
Service-life extension (with SCMs/admixtures)	Improved durability	Reduced maintenance
Reduced carbon footprint	Lower extraction and cement demand	Climate change mitigation

Source: Compiled by the Author based on Silva et al. (2014); Habert et al. (2020); UNEP (2024); Akbulut et al. (2025).

Table 2.7 Summary of Recent Research on Recycled Aggregate Concrete (2018–2025)

Author	Research Focus	Major Findings	Research Limitation
Thomas et al. (2018)	Mechanical performance	30–50% RCA acceptable	Limited durability evaluation
Guo et al. (2018)	ITZ characteristics	ITZ governs RAC durability	Limited field applications
Wang et al. (2021)	RCA treatment	Pre-treatment improves quality	Treatment cost
Zhao et al. (2021)	SCM incorporation	Improves strength and chloride resistance	Limited crystalline admixture studies
Luo et al. (2022)	Durability review	Service life controlled by permeability	Need for performance-based standards
Akbulut et al. (2025)	Critical RAC review	SCMs and pre-treatment essential	Need integrated RAC-SCM-CA studies

Source: Compiled by the Author based on Thomas et al. (2018); Guo et al. (2018); Wang et al. (2021); Zhao et al. (2021); Luo et al. (2022); Akbulut et al. (2025).

Table 2.8 Research Gaps Identified from the Literature

Existing Research	**Research Gap**	**Present Investigation**
RAC with SCMs	Limited crystalline admixture application	✓
Mechanical properties	Limited simultaneous durability evaluation	✓
Durability studies	Limited sustainability assessment	✓
Separate RAC and GPC studies	Few comparative investigations	✓
RCA pretreatment	Limited dosage optimization	✓
Laboratory investigations	Limited practical design recommendations	✓

Source: Developed by the Author based on the reviewed literature.

The literature clearly demonstrates that recycled aggregate concrete has evolved from a waste management alternative into a high-performance sustainable construction material. Modern research emphasizes durability enhancement through supplementary cementitious materials, aggregate pretreatment, and pore-refinement technologies rather than focusing solely on compressive strength. Service-life extension has emerged as a key sustainability indicator because durable concrete reduces maintenance frequency, conserves resources, and minimizes life-cycle carbon emissions. Recent reviews recommend integrating material optimization, durability testing, and life-cycle assessment within a unified framework to achieve reliable and environmentally sustainable concrete structures.

Despite these advancements, several knowledge gaps remain. Most published studies investigate recycled aggregate concrete, geopolymer concrete, supplementary cementitious materials, and crystalline admixtures independently. Direct comparisons between M35 recycled aggregate concrete containing 60% recycled coarse aggregate and M35 geopolymer concrete, incorporating identical crystalline admixture dosages of 0%, 0.8%, and 1.0%, are rarely reported. Furthermore, few studies simultaneously evaluate fresh properties, mechanical performance, durability characteristics, and sustainability indicators within the same experimental programme. These limitations justify the present research, which aims to establish an integrated framework for developing durable, low-carbon, and sustainable concrete systems suitable for future resilient infrastructure.

2.4 Geopolymer Concrete (GPC): A Sustainable Alternative to Ordinary Portland Cement Concrete

The increasing global demand for sustainable infrastructure and the urgent need to reduce greenhouse gas emissions have accelerated research into Geopolymer Concrete (GPC) as an environmentally friendly alternative to Ordinary Portland Cement (OPC) concrete. Portland cement manufacturing alone contributes approximately 7–8% of global anthropogenic CO_2 emissions, primarily because of limestone calcination and the high-temperature clinker production process. Geopolymer concrete addresses this environmental challenge by replacing Portland cement with aluminosilicate-rich industrial by-products such as Class F fly ash, Ground Granulated Blast Furnace Slag (GGBS), metakaolin, rice husk ash (RHA), and silica fume, which are activated using alkaline solutions to produce a high-performance binder. This technology significantly reduces clinker consumption, diverts industrial waste from landfills, and supports circular economy principles while maintaining excellent engineering performance.

Unlike conventional cement hydration, geopolymer concrete develops strength through Geopolymerization, a chemical process in which aluminosilicate materials dissolve in a highly alkaline environment and subsequently polymerize to form a three-dimensional aluminosilicate network. The primary reaction products are sodium aluminosilicate hydrate (N–A–S–H) gel and, in calcium-rich systems containing GGBS, calcium aluminosilicate hydrate (C–A–S–H) gel. These reaction products produce a dense microstructure with significantly lower porosity and permeability than conventional Portland cement paste, resulting in superior mechanical properties, chemical resistance, and long-term durability.

Recent investigations demonstrate that optimized geopolymer mixtures can reduce embodied carbon by 40–80%, depending on the precursor material, alkaline activator, curing regime, and transportation distance. However, the environmental benefits are also influenced by the production of sodium hydroxide and sodium silicate activators, which contribute to the overall life-cycle impacts. Consequently, current research increasingly emphasizes optimization of activator composition, ambient curing techniques, and utilization of locally available industrial by-products to maximize sustainability while minimizing environmental burdens.

Figure 2.6 Geopolymerization Mechanism

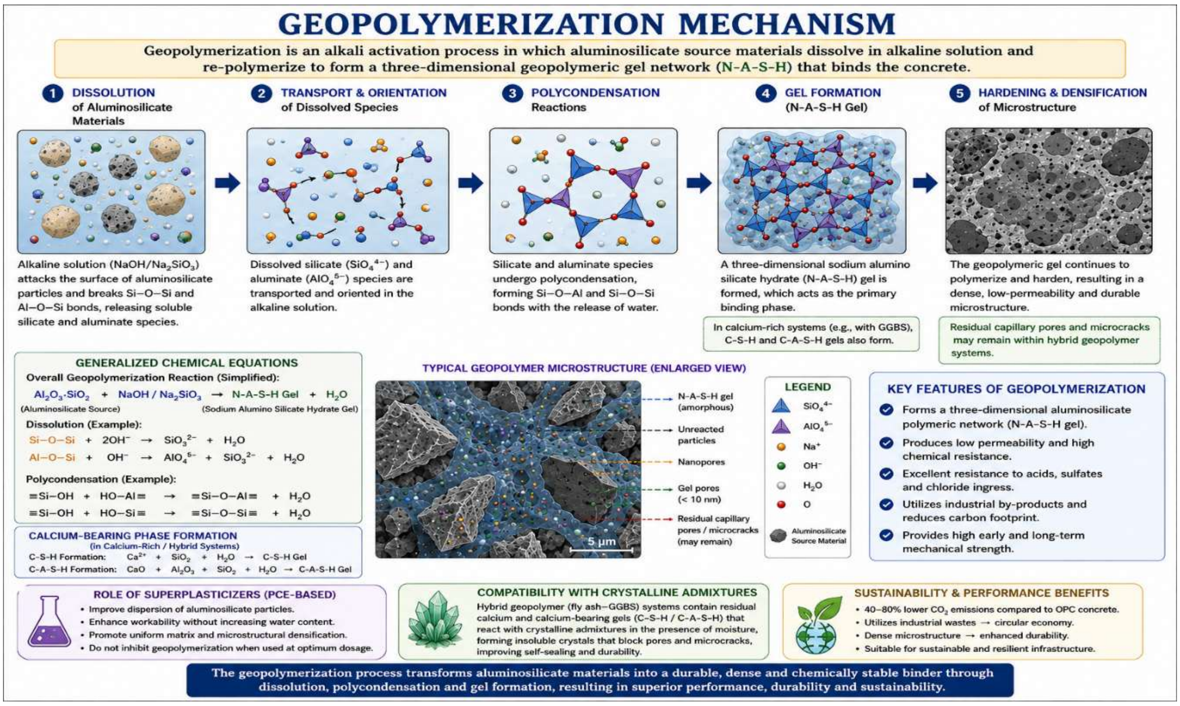


Figure 2.6. Schematic illustration of the Geopolymerization process showing dissolution, transport, polycondensation, gel formation, and hardening.

Source: Adapted from Davidovits (1991); Duxson et al. (2007); Provis (2018); Provis and van Deventer (2014).

Table 2.9 Stages of the Geopolymerization Process

Stage	Process	Description	Engineering Significance
1	Dissolution	Alkaline solution dissolves silica and alumina from precursor materials	Releases reactive species
2	Transportation	Dissolved ions migrate through the alkaline medium	Promotes homogeneous reaction
3	Polycondensation	Silicate and aluminate species combine to form polymer chains	Formation of aluminosilicate network
4	Gel Formation	N–A–S–H and C–A–S–H gels develop	Primary binding phase

5	Hardening	Continuous polymerization densifies the matrix	Strength and durability development

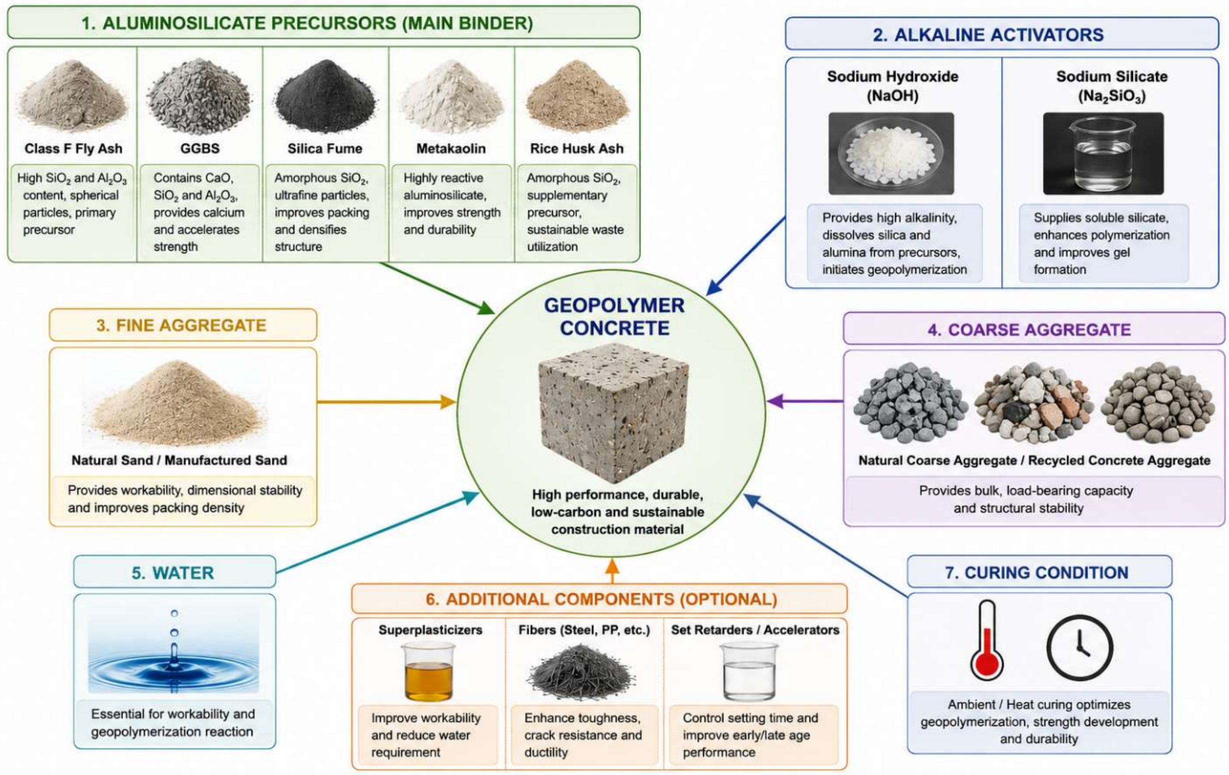
Source: Compiled by the Author based on Davidovits (1991); Duxson et al. (2007); Provis (2018).

2.4.1 Raw Materials Used in Geopolymer Concrete

The performance of geopolymer concrete depends primarily on the chemical composition of the precursor materials and the alkaline activator. The most widely used precursor is Class F fly ash, owing to its high amorphous silica and alumina content, spherical particle shape, and excellent workability. However, fly ash-based geopolymer concrete often develops relatively slow early-age strength under ambient curing conditions. To overcome this limitation, researchers commonly incorporate Ground Granulated Blast Furnace Slag (GGBS), whose calcium content accelerates Geopolymerization and promotes the formation of additional C–A–S–H gel. The combination of fly ash and GGBS therefore provides both high early strength and excellent long-term durability.

Silica fume has recently become an important component of ternary geopolymer systems because of its ultrafine particle size and high amorphous silica content. Acting simultaneously as a reactive pozzolan and micro-filler, silica fume refines pore structure, improves particle packing, strengthens the Geopolymeric matrix, and significantly enhances resistance to chloride penetration and water permeability. Recent literature also reports increasing utilization of rice husk ash, metakaolin, and other agricultural or industrial wastes as sustainable geopolymer precursors, further expanding the applicability of alkali-activated concrete systems.

Figure 2.7 Major Constiuents of Geopolymer Concrete



Source: Adapted from Provis and van Deventer (2014); Provis (2018); Davidovits (1991).

Figure 2.7 Major Constituents of Geopolymer Concrete

Figure 2.7. Principal constituents of geopolymer concrete including aluminosilicate precursors, alkaline activators, aggregates, and water.

Source: Adapted from Provis and van Deventer (2014); Provis (2018); Davidovits (1991).

Table 2.10 Common Aluminosilicate Materials Used in Geopolymer Concrete

Material	**Major Chemical Constituents**	**Primary Function**	**Major Benefit**
Class F Fly Ash	SiO_2, Al_2O_3	Main precursor	Low heat, good workability
GGBS	CaO, SiO_2, Al_2O_3	Calcium source	High early strength
Silica Fume	Amorphous SiO_2	Micro-filler	Dense microstructure
Metakaolin	Reactive Al_2O_3, SiO_2	High-reactivity precursor	High strength
Rice Husk Ash	Amorphous SiO_2	Supplementary precursor	Sustainable waste utilization
Sodium Hydroxide (NaOH)	Alkali activator	Dissolves aluminosilicates	Initiates Geopolymerization
Sodium Silicate (Na_2SiO_3)	Soluble silicate	Polymerization enhancer	Improves gel formation

Source: Compiled by the Author based on Davidovits (1991); Provis and van Deventer (2014); Provis (2018); recent geopolymer reviews.

Summary

The literature confirms that geopolymer concrete represents one of the most promising alternatives to conventional Portland cement concrete because of its low carbon footprint, efficient utilization of industrial by-products, and superior durability. The Geopolymerization process produces a dense N–A–S–H/C–A–S–H gel network that enhances mechanical performance while significantly reducing permeability. Recent research has focused on optimizing ternary binder systems incorporating fly ash, GGBS, and silica fume to improve early-age strength, durability, and sustainability, forming the foundation for the experimental investigation presented in this thesis.

2.4.2 Mechanical Performance and Durability of Geopolymer Concrete

The superior engineering performance of Geopolymer Concrete (GPC) has positioned it as one of the most promising sustainable alternatives to Ordinary Portland Cement (OPC) concrete. Unlike OPC concrete, whose strength primarily depends on calcium silicate hydrate (C–S–H) formation, Geopolymer concrete derives its mechanical properties from the development of a dense three-dimensional aluminosilicate network consisting mainly of Sodium Aluminosilicate Hydrate (N–A–S–H) gel and, in calcium-rich systems, Calcium Aluminosilicate Hydrate (C–A–S–H) gel. The dense geopolymeric matrix exhibits lower porosity, fewer interconnected capillary pores, and a stronger aggregate–binder interface than conventional cement paste, thereby improving compressive strength, tensile strength, durability, and dimensional stability (Davidovits, 1991; Duxson et al., 2007; Provis, 2018).

Recent investigations indicate that Geopolymer concrete incorporating Class F fly ash, GGBS, and silica fume can achieve compressive strengths exceeding 40–80 MPa, depending on precursor composition, alkaline activator concentration, curing temperature, and water-to-binder ratio. While fly ash contributes to long-term strength development through gradual Geopolymerization, GGBS significantly accelerates early-age strength because of its calcium content, promoting additional C–A–S–H gel formation. Silica fume further improves particle packing and microstructural densification owing to its ultrafine particle size and highly reactive amorphous silica. Consequently, ternary geopolymer binder systems generally outperform binary mixtures with respect to both mechanical performance and durability (Rashad, 2013; Ye et al., 2017; Zhang et al., 2020).

The tensile and flexural strengths of Geopolymer concrete are also considerably improved due to the continuous aluminosilicate gel matrix and the enhanced bond between aggregates and binder. Several experimental studies have reported that optimized geopolymer concrete exhibits 10–20% higher splitting tensile strength and 15–25% higher flexural strength than conventional OPC concrete of comparable compressive strength. These improvements are attributed to reduced microcracking, enhanced crack-bridging capacity, and improved load transfer efficiency throughout the geopolymeric network (Ryu et al., 2013; Zhang et al., 2020).

Figure 2.8 :Geopolymer Concrete Microstructure

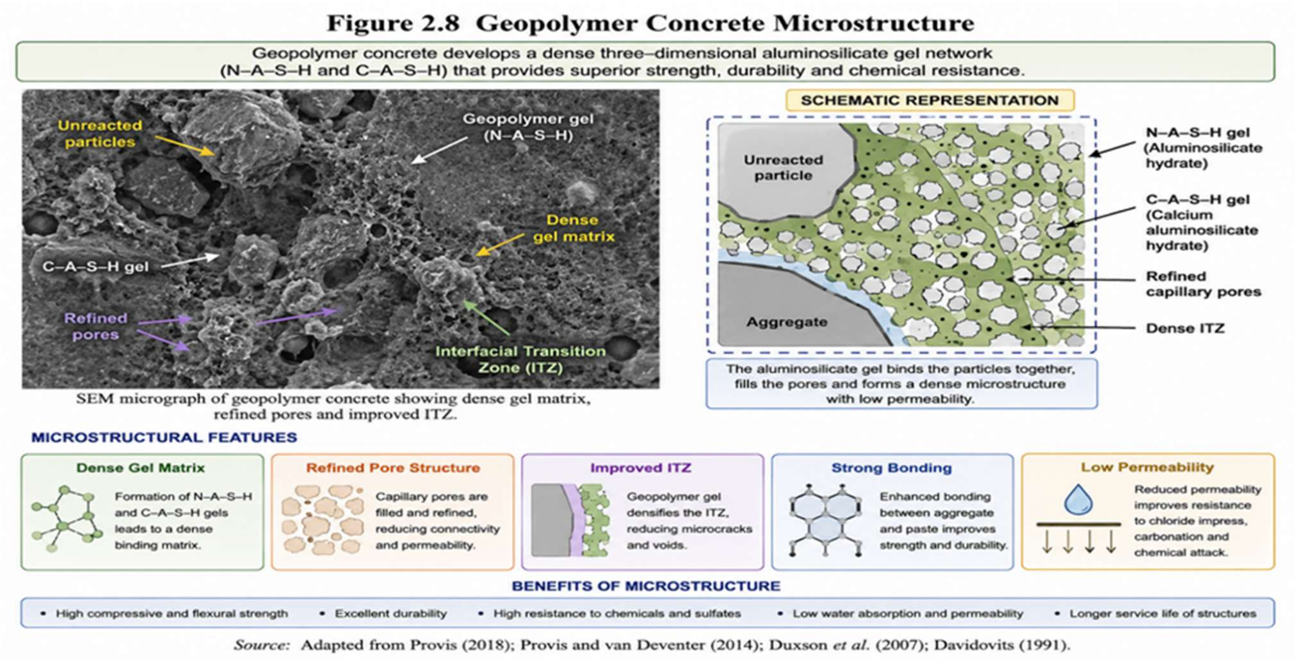


Figure 2.8. Schematic representation of the dense geopolymer microstructure showing partially reacted fly ash particles surrounded by N–A–S–H and C–A–S–H gel.

Source: Adapted from Duxson et al. (2007); Provis (2018); Zhang et al. (2020).

Table 2.11 Mechanical Properties of Geopolymer Concrete

Property	**Conventional OPC Concrete**	**Geopolymer Concrete**	**Engineering Benefit**
Compressive Strength (MPa)	30–60	40–80	Higher structural capacity
Splitting Tensile Strength (MPa)	2.5–4.5	3.0–5.5	Better crack resistance
Flexural Strength (MPa)	4–6	5–8	Improved bending performance
Elastic Modulus (GPa)	25–35	28–38	Higher stiffness
Drying Shrinkage	Moderate	Low	Improved dimensional stability
Heat of Reaction	High	Low	Reduced thermal cracking

Source: Compiled by the Author based on Provis (2018); Zhang et al. (2020); Ryu et al. (2013); Rashad (2013).

2.4.3 Durability Performance of Geopolymer Concrete

Durability is widely recognized as one of the greatest advantages of geopolymer concrete. Owing to its compact aluminosilicate gel network and refined pore structure, GPC exhibits significantly lower permeability than conventional OPC concrete. The reduced pore connectivity restricts the movement of water, chlorides, sulphate's, and carbon dioxide, thereby minimizing reinforcement corrosion and extending service life. Numerous experimental studies have demonstrated that geopolymer concrete performs exceptionally well under aggressive environmental exposure, including marine environments, sulphate-rich soils, industrial wastewater, and high-temperature applications (Shi et al., 2011; Provis, 2018).

Rapid Chloride Permeability Test (RCPT) results consistently show that optimized geopolymer mixtures exhibit very low chloride ion penetrability, often recording values below 1000 coulombs, compared with 2000–4000 coulombs for conventional OPC concrete of similar strength. Similarly, water absorption and absorptivity are substantially lower because of the dense Geopolymeric matrix, while carbonation depth remains relatively limited under normal atmospheric exposure. In addition, geopolymer concrete demonstrates remarkable resistance to sulphuric acid, hydrochloric acid, and sulphate attack because the aluminosilicate gel network contains significantly lower calcium hydroxide than Portland cement systems, reducing susceptibility to chemical degradation (Zhang et al., 2020; Habert et al., 2020).

One of the most significant advantages of geopolymer concrete is its excellent thermal stability. Unlike Portland cement concrete, which experiences severe strength loss above 400°C due to decomposition of calcium hydroxide and C–S–H gel, geopolymer concrete retains much of its structural integrity at temperatures exceeding 600–800°C. The ceramic-like aluminosilicate structure exhibits excellent fire resistance, reduced thermal cracking, and improved residual strength, making geopolymer concrete particularly suitable for industrial structures, tunnels, nuclear facilities, and fire-resistant construction (Provis, 2018).

Figure 2.9 Comparison of Hydration Products in OPC and Geopolymer Concrete

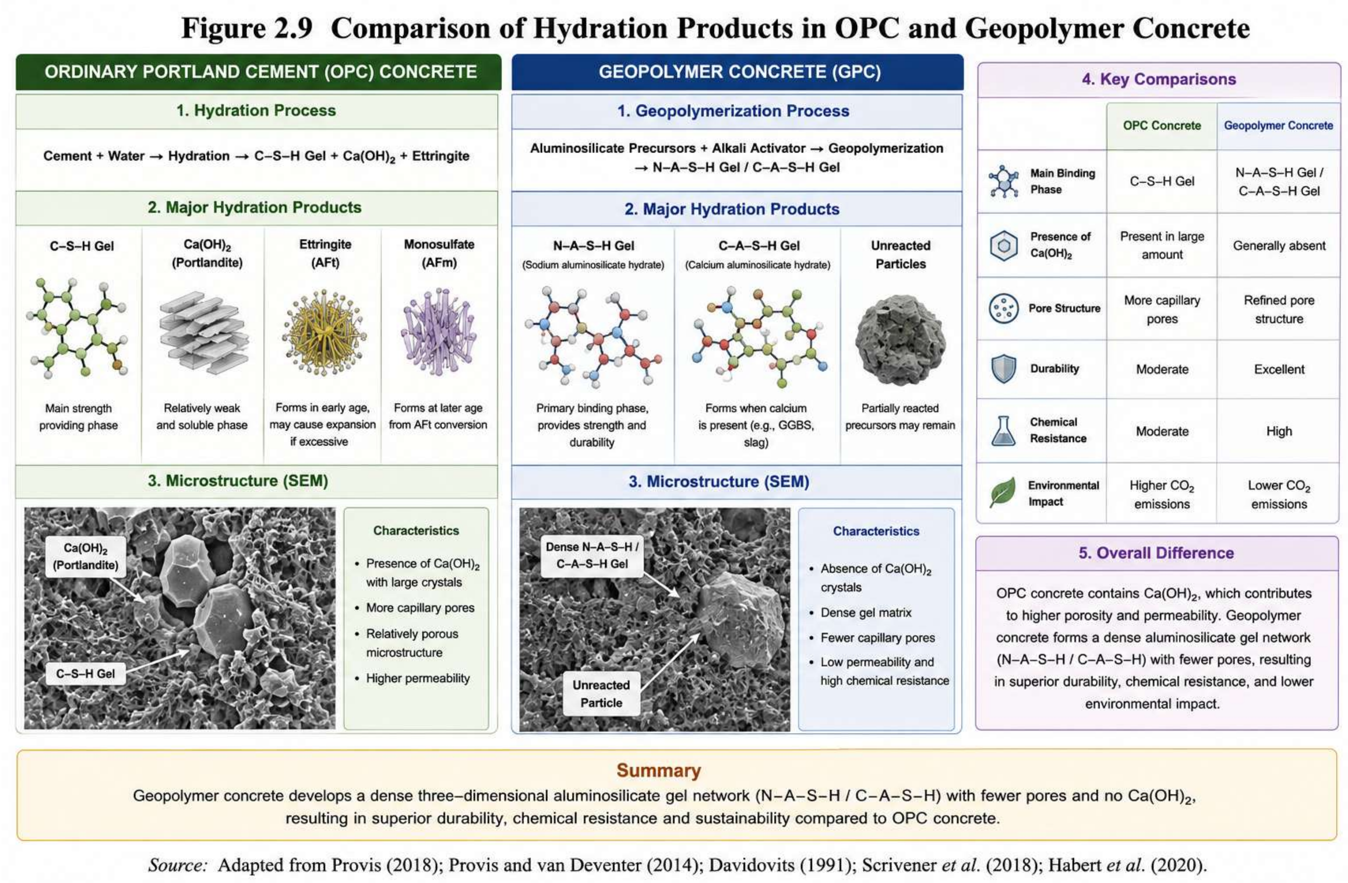


Figure 2.9. Comparison between Portland cement hydration products and geopolymer reaction products illustrating the denser aluminosilicate network in geopolymer concrete.

Source: Adapted from Davidovits (1991); Duxson et al. (2007); Provis (2018).

Table 2.12 Durability Comparison Between OPC Concrete and Geopolymer Concrete

Durability Parameter	OPC Concrete	Geopolymer Concrete	Performance
Water Absorption	Moderate	Low	Excellent
RCPT (Coulombs)	2000–4000	<1000	Very Low Chloride Penetration

Sulphate Resistance	Moderate	Excellent	Superior
Acid Resistance	Poor–Moderate	Excellent	Superior
Carbonation Resistance	Moderate	High	Improved durability
Elevated Temperature Resistance	Moderate	Excellent	Fire resistant
Service Life	50–75 years	75–100+ years*	Longer durability

*Depending on mix composition, exposure conditions, and design practices.

Source: Compiled by the Author based on Shi et al. (2011); Provis (2018); Zhang et al. (2020); Habert et al. (2020).

Critical Analysis

The recent literature demonstrates that geopolymer concrete offers substantial advantages over conventional Portland cement concrete in terms of mechanical strength, durability, and environmental sustainability. The formation of dense N–A–S–H and C–A–S–H gels produces a refined pore structure that significantly reduces permeability and improves resistance to chloride ingress, sulphate attack, acid exposure, and elevated temperatures. The incorporation of GGBS and silica fume further enhances early-age strength and long-term durability, making ternary geopolymer systems particularly attractive for structural applications.

Despite these advances, several limitations remain. Most published studies have focused on optimizing geopolymer binder chemistry, whereas comparatively fewer investigations have evaluated the combined effects of crystalline admixtures on geopolymer concrete. Furthermore, direct comparative studies involving M35 geopolymer concrete incorporating Class F fly ash, GGBS, silica fume, and crystalline admixtures (0%, 0.8%, and 1.0%) under identical experimental conditions remain limited. The absence of standardized mix-design procedures and long-term field validation also continues to restrict widespread industrial implementation. Addressing these research gaps forms a major objective of the present study.

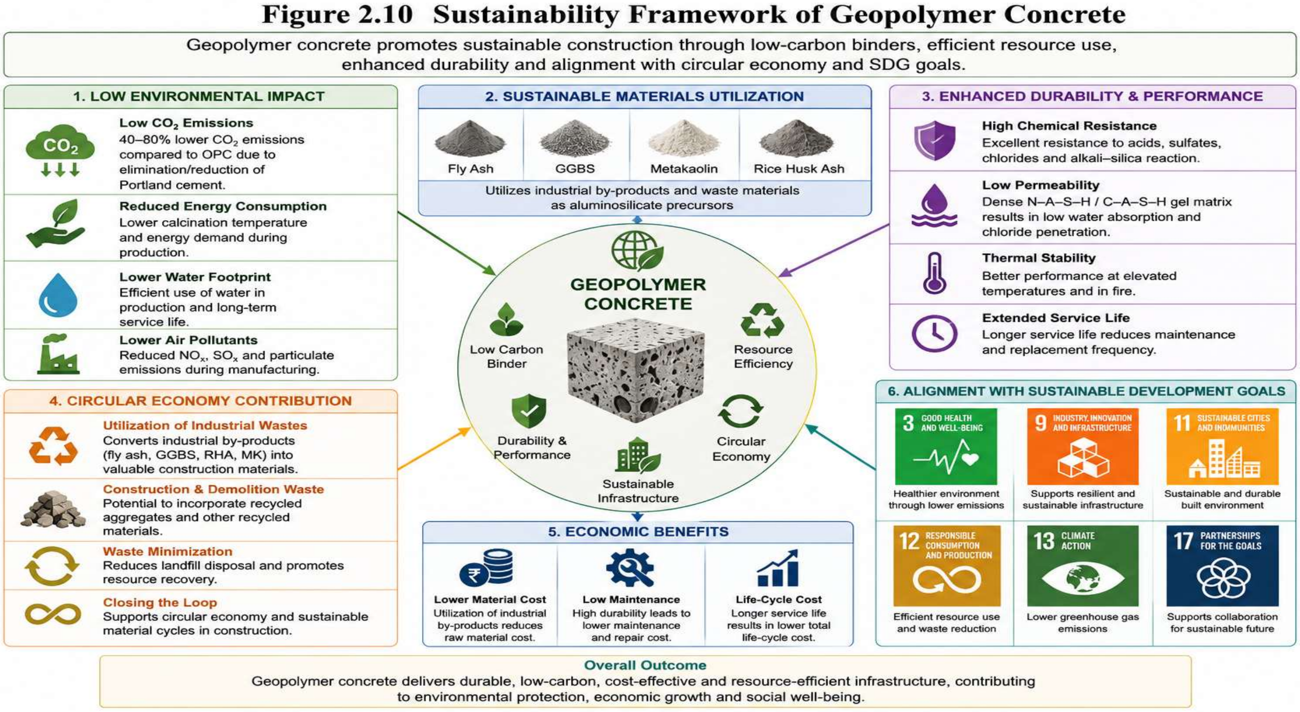
2.4.4 Sustainability, Recent Developments and Future Perspectives of Geopolymer Concrete

The growing emphasis on sustainable construction has positioned Geopolymer Concrete (GPC) as one of the most promising alternatives to conventional Portland cement concrete. Unlike Ordinary Portland Cement (OPC), whose manufacture requires energy-intensive clinker production and releases significant quantities of carbon dioxide (CO_2), geopolymer concrete utilizes industrial by-products such as Class F fly ash, Ground Granulated Blast Furnace Slag (GGBS), silica fume, and other aluminosilicate-rich materials as binder precursors. These industrial wastes are activated by alkaline solutions, thereby eliminating or substantially reducing Portland cement consumption. Consequently, geopolymer technology simultaneously addresses two major environmental challenges: reducing industrial waste disposal and lowering greenhouse gas emissions associated with cement production (Davidovits, 1991; Habert et al., 2020; Provis, 2018).

Life Cycle Assessment (LCA) studies consistently demonstrate that geopolymer concrete can reduce embodied carbon emissions by 40–80%, depending on precursor type, activator composition, transportation distance, and curing conditions. The greatest environmental benefits are achieved when locally available industrial by-products are utilized and ambient curing techniques are adopted, thereby minimizing energy consumption and transportation impacts. Furthermore, the utilization of fly ash and GGBS diverts significant quantities of industrial waste from landfills while reducing dependence on non-renewable limestone resources. These advantages strongly support the objectives of the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) (Habert et al., 2020; UNEP, 2024).

Beyond carbon reduction, geopolymer concrete contributes to sustainability through its superior durability. The dense aluminosilicate gel network significantly reduces permeability, chloride diffusion, carbonation, sulfate attack, and water ingress compared with conventional OPC concrete. These characteristics delay reinforcement corrosion, reduce maintenance frequency, and extend structural service life. Recent performance-based sustainability frameworks emphasize that extending service life often provides greater environmental benefits than merely reducing initial embodied carbon because maintenance, repair, and replacement activities contribute substantially to total life-cycle emissions. Therefore, durability improvement and environmental sustainability should be considered complementary objectives in modern concrete design (Scrivener et al., 2018; Habert et al., 2020).

Figure 2.10 Sustainability Framework of Geopolymer Concrete



Source: Adapted from Provis (2018); Provis and van Deventer (2014); Habert *et al.* (2020); UNEP (2024); World Green Building Council (2023).

Figure 2.10. Sustainability framework illustrating the environmental and engineering benefits of geopolymer concrete through industrial waste utilization, carbon reduction, durability enhancement, and life-cycle performance.

Source: Adapted from Davidovits (1991); Provis (2018); Habert et al. (2020); UNEP (2024).

2.4.5 Recent Developments in Geopolymer Concrete

During the past decade, geopolymer research has progressed beyond laboratory-scale investigations toward practical structural applications. Recent studies have focused on ambient-cured geopolymer concrete, ternary and quaternary binder systems, fiber-reinforced geopolymer composites, 3D-printable geopolymer concrete, and carbon-neutral binder technologies. The incorporation of silica fume, nano-silica, basalt fibers, steel fibers, and recycled aggregates has significantly enhanced mechanical performance, fracture toughness, and durability while maintaining low environmental impacts.

Among these developments, ternary binder systems consisting of Class F fly ash, GGBS, and silica fume have attracted considerable attention because they combine the excellent workability of fly ash, the early-age strength of GGBS, and the pore-refining capability of silica fume. These blended systems exhibit superior compressive strength, reduced chloride permeability, lower drying shrinkage, and improved long-term durability compared with binary geopolymer mixtures. Recent studies have also demonstrated that ambient-cured ternary geopolymer concrete can achieve structural-grade performance comparable to heat-cured systems, making large-scale field implementation increasingly feasible (Akbulut et al., 2025; Zhang et al., 2020).

Another emerging research area involves the incorporation of crystalline admixtures into geopolymer concrete. Although crystalline admixtures have demonstrated excellent waterproofing performance in Portland cement systems, their compatibility with geopolymeric binders remains insufficiently understood. Preliminary investigations indicate that crystalline admixtures may further reduce pore connectivity and improve water tightness; however, comprehensive experimental validation remains limited. Consequently, additional studies evaluating the influence of crystalline admixture dosage on the mechanical, durability, and sustainability performance of geopolymer concrete are strongly recommended.

Table 2.13 Sustainability Benefits of Geopolymer Concrete

Sustainability Indicator	**Contribution of Geopolymer Concrete**	**Engineering Benefit**
Portland cement reduction	70–100% replacement	Significant CO_2 reduction
Industrial waste utilization	Fly ash, GGBS, silica fume	Circular economy
Lower embodied carbon	Reduced clinker production	Climate change mitigation

Lower energy consumption	Ambient curing (optimized mixes)	Improved sustainability
Extended service life	High durability	Reduced maintenance
Reduced landfill disposal	Utilization of industrial by-products	Resource conservation
High chemical resistance	Reduced deterioration	Longer structural life

Source: Compiled by the Author based on Davidovits (1991); Provis (2018); Habert et al. (2020); UNEP (2024).

Table 2.14 Summary of Recent Research on Geopolymer Concrete (2018–2026)

Author	Research Focus	Major Findings	Research Limitation
Provis (2018)	Alkali-activated materials	Dense N–A–S–H gel improves durability	Limited field implementation
Zhang et al. (2020)	Ternary geopolymer binders	Higher strength and lower permeability	Limited large-scale validation
Habert et al. (2020)	Life-cycle assessment	40–80% reduction in embodied CO_2	Activator production impacts
Akbulut et al. (2025)	Sustainable geopolymer systems	Ternary blends enhance mechanical and durability performance	Limited crystalline admixture studies
Recent Reviews (2024–2026)	Ambient-cured geopolymer concrete	Improved practicality for structural applications	Need for standardized design methods

Source: Compiled by the Author based on the cited literature.

2.4.6 Critical Analysis and Research Gap

The literature confirms that geopolymer concrete has become one of the most promising low-carbon construction materials owing to its excellent mechanical properties, superior durability, and substantially lower environmental impact than conventional Portland cement concrete. The combination of fly ash, GGBS, and silica fume produces a dense aluminosilicate matrix capable of resisting chloride ingress, sulfate attack, acid exposure, and elevated temperatures while significantly reducing embodied carbon emissions. These characteristics make geopolymer concrete particularly suitable for sustainable infrastructure applications requiring long service life and reduced maintenance.

Despite these significant advances, several knowledge gaps remain. Most published investigations have focused on optimizing geopolymer binder composition or alkaline activator concentration rather than evaluating durability-enhancing admixtures. In particular, the interaction between crystalline admixtures and ternary geopolymer systems remains insufficiently understood. Furthermore, relatively few studies have directly compared geopolymer concrete with recycled aggregate concrete under identical experimental conditions while simultaneously evaluating fresh properties, compressive strength, durability indicators (RCPT, water permeability, carbonation, sulphate resistance), and sustainability metrics.

Another limitation is the absence of standardized geopolymer mix-design procedures equivalent to IS 10262:2019 for conventional concrete. Variations in precursor chemistry, activator composition, curing conditions, and testing methodologies continue to produce inconsistent results among published studies. Therefore, comprehensive comparative investigations incorporating M35 geopolymer concrete, Class F fly ash, GGBS, silica fume, and crystalline admixtures at 0%, 0.8%, and 1.0% dosages under identical experimental conditions are still limited.

The present research addresses these gaps by comparing M35 Recycled Aggregate Concrete (60% RCA) and M35 Ternary Geopolymer Concrete modified with identical crystalline admixture dosages. The investigation integrates fresh properties, mechanical performance, durability characteristics, and sustainability assessment within a unified experimental framework, thereby contributing toward the development of durable, low-carbon, and environmentally sustainable concrete suitable for resilient infrastructure.

2.5 Crystalline Admixtures for Durability Enhancement of Sustainable Concrete

Concrete durability is primarily governed by its resistance to the ingress of water and aggressive substances through interconnected pores, capillary channels, and microcracks. Although concrete is generally considered a durable construction material, its porous microstructure allows the penetration of chlorides, sulphate's, carbon dioxide, acids, and moisture, which gradually deteriorate the cement matrix and initiate reinforcement corrosion. These deterioration mechanisms significantly reduce structural service life and increase maintenance costs, making durability one of the most important factors in sustainable infrastructure development. Consequently, modern concrete technology has increasingly focused on permeability-reducing admixtures capable of enhancing long-term durability rather than merely increasing compressive strength (Neville, 2011; Mehta & Monteiro, 2014).

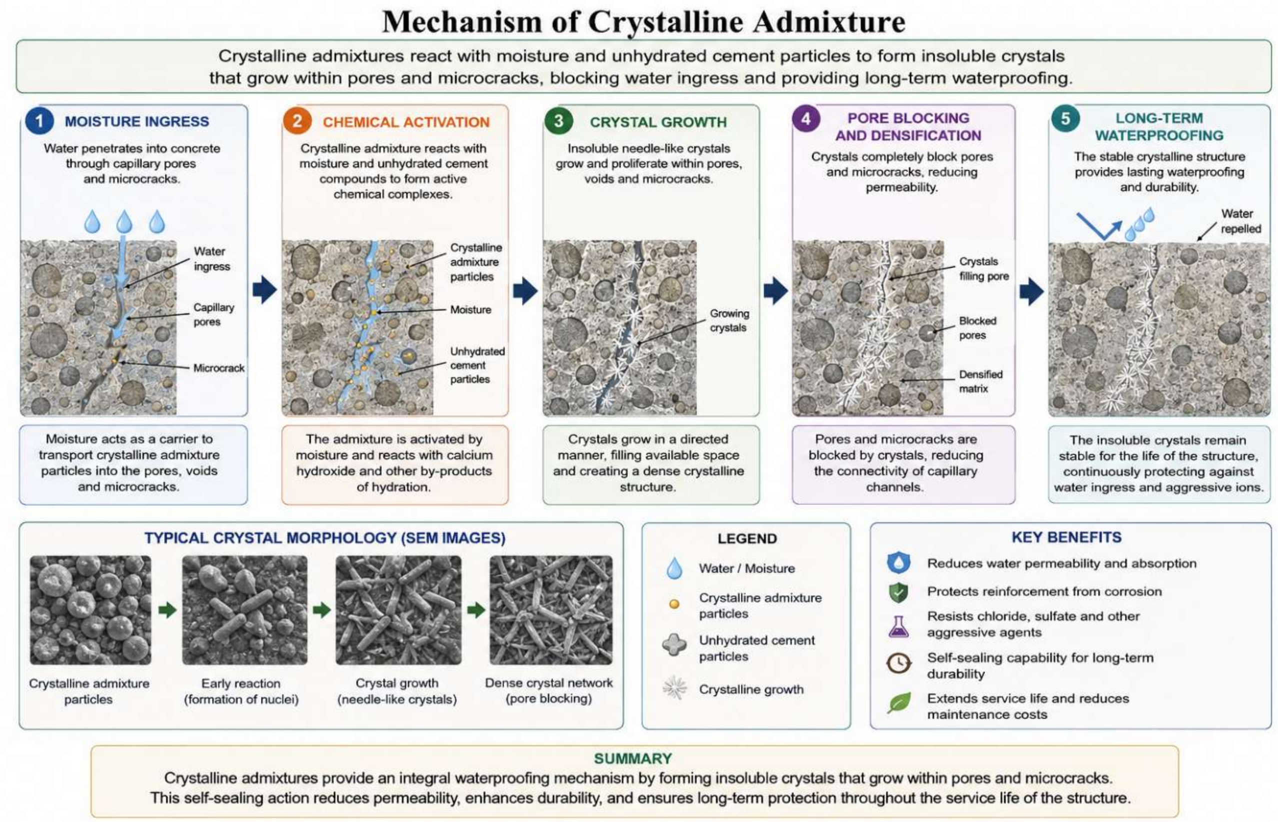
Among the available durability-enhancing technologies, crystalline admixtures (CAs) have emerged as one of the most effective permeability-reducing materials. Unlike conventional waterproofing systems that form only a surface barrier, crystalline admixtures function throughout the concrete matrix by chemically reacting with moisture, calcium hydroxide, and unhydrated cement particles to form insoluble needle-like crystalline products. These crystals grow within capillary pores, microcracks, and voids, permanently blocking water migration pathways while allowing water vapour transmission. This unique self-sealing mechanism distinguishes crystalline admixtures from conventional waterproofing materials and significantly improves long-term durability (ACI Committee 212.3R-16; Richardson, 2008).

The application of crystalline admixtures has increased rapidly in tunnels, dams, water-retaining structures, basements, marine structures, wastewater treatment plants, and bridge decks because of their ability to reduce permeability, improve resistance to chloride penetration, and extend service life. Recent studies also indicate that crystalline admixtures contribute to sustainability by reducing repair frequency, minimizing maintenance-related resource consumption, and lowering life-cycle environmental impacts. Consequently, crystalline admixtures are increasingly regarded as an integral component of durable and sustainable concrete rather than merely a waterproofing additive (Van Belleghem et al., 2018).

Figure 2.11 Mechanism of Crystalline Admixture Action

Figure 2.11. Mechanism of crystalline admixture showing moisture ingress, chemical activation, crystal growth, pore blocking, and long-term waterproofing.

Source: Adapted from ACI Committee 212.3R-16 (2016); Richardson (2008); Van Belleghem et al. (2018)



Source: Adapted from Neville (2011); Mehta and Monteiro (2014); Kryton International Inc. (2023); Habert *et al.* (2020).

Table 2.15: Types of Permeability-Reducing Admixtures

Admixture Type	Working Principle	Primary Application	Limitation
Hydrophobic Admixture	Repels water	General waterproofing	Limited crack sealing
Pore Blocking Admixture	Reduces capillary size	Water-retaining structures	Limited self-healing
Crystalline Admixture	Crystal growth within pores	Waterproof concrete	Requires moisture activation
Polymer Admixture	Forms polymer film	Repair mortars	Higher cost
Latex Admixture	Improves adhesion	Thin overlays	Lower chemical resistance

Source: Compiled by the Author based on ACI Committee 212.3R-16 (2016); Neville (2011); Mehta & Monteiro (2014).

2.5.1 Chemical Mechanism of Crystalline Admixtures

Crystalline admixtures consist of proprietary blends of reactive chemicals that remain dormant within the hardened concrete until activated by moisture. When water penetrates the concrete, these chemicals react with calcium hydroxide [$Ca(OH)_2$], unhydrated cement particles, and soluble calcium ions to produce insoluble crystalline structures that progressively fill capillary pores, micro voids, and microcracks. As crystal growth continues, interconnected pore networks become discontinuous, significantly reducing permeability while maintaining the vapour permeability necessary for concrete breathability (Richardson, 2008).

Unlike conventional waterproof membranes, which protect only the concrete surface, crystalline admixtures become an integral part of the concrete matrix. If new microcracks develop during the service life, subsequent exposure to moisture reactivates the remaining chemicals, promoting additional crystal formation and restoring water tightness. This autonomous self-sealing mechanism is one of the most significant advantages of crystalline technology and has attracted considerable attention in modern durability research (ACI Committee 212.3R-16; Sisomphon et al., 2012).`

2.5.2. Self-Healing Mechanism of Crystalline Admixtures and the Need for Crystalline Admixtures in SCM-Based Concrete

1. Self-Healing Mechanism of Crystalline Admixtures

Crystalline admixtures (CA) are hydrophilic waterproofing materials added to concrete during mixing. They contain reactive chemicals that remain dormant within the hardened concrete. When water penetrates through pores or microcracks, these chemicals become activated and react with moisture, unhydrated cement particles, calcium hydroxide ($Ca(OH)_2$), and other hydration products. This reaction produces insoluble needle-like and dendritic crystals that grow deep into the capillary network and cracks, blocking the pathways for water and harmful ions.

Unlike conventional waterproofing systems that merely coat the surface, crystalline admixtures create an internal waterproofing system. The crystals continue to grow whenever moisture is available, allowing the concrete to repeatedly seal newly formed microcracks, typically up to 0.4–0.5 mm, depending on the concrete mix, crack conditions, and curing environment. This autonomous self-healing process significantly reduces water permeability, chloride ingress, sulfate attack, and reinforcement corrosion, thereby improving the durability and service life of concrete structures.

2. Self-Healing Process

Water enters through pores or microcracks

↓

Dormant crystalline chemicals become activated

↓

Reaction with $Ca(OH)_2$, moisture and hydration products

↓

Formation of insoluble needle-like crystals

↓

Crystal growth inside pores and cracks

↓

Capillary network becomes blocked

↓

Water and chloride ingress prevented

↓

Repeated self-healing whenever moisture re-enters

3. Why Are Crystalline Admixtures Required When SCMs Are Already Used?

Supplementary Cementitious Materials (SCMs) and Crystalline Admixtures (CA) improve durability through different mechanisms, making them complementary rather than redundant.

Supplementary Cementitious Materials (SCMs)	**Crystalline Admixtures (CA)**
Reduce initial pore size through pozzolanic reactions	Seal pores and microcracks after concrete hardens
Consume calcium hydroxide to produce additional C-S-H gel	React with available moisture and hydration products to form insoluble crystals
Improve compressive strength and reduce permeability	Provide active waterproofing and self-healing
Improve microstructure during hydration	Continue functioning throughout the service life whenever moisture is present
Cannot autonomously heal new cracks	Continuously seal newly formed microcracks
Improve durability passively	Improve durability actively

4. Why SCM Alone Is Not Sufficient

- Drying shrinkage and thermal stresses can still generate microcracks.
- Service loads and structural movements may create new cracks after hardening.
- SCMs refine the pore structure but do not actively seal cracks once they develop.
- Water and aggressive ions can still penetrate through these cracks.
- Reinforcement corrosion may initiate if cracks remain open.
- Therefore, SCMs primarily provide preventive durability, whereas crystalline admixtures provide corrective and continuous durability through self-healing.

5. Synergistic Mechanism of SCM + Crystalline Admixture

SCMs contribute by refining pore structure, producing additional C-S-H gel, reducing permeability, lowering heat of hydration, and increasing long-term strength. Crystalline admixtures contribute by blocking remaining capillary pores, sealing microcracks throughout the concrete service life, reducing water absorption and chloride penetration, providing repeated moisture-activated self-healing, and extending the service life of reinforced concrete.

6. Integrated Durability Enhancement Mechanism

SCM Addition (Fly Ash / GGBS / Silica Fume)

|

▼

Pozzolanic Reaction

|

▼

Additional C-S-H Gel

|

▼

Reduced Porosity

|

▼

Microcracks Develop During Service

|

▼

Moisture Penetration

|

▼

Crystalline Chemicals Activated

|

▼

Crystal Growth in Pores and Cracks

|

▼

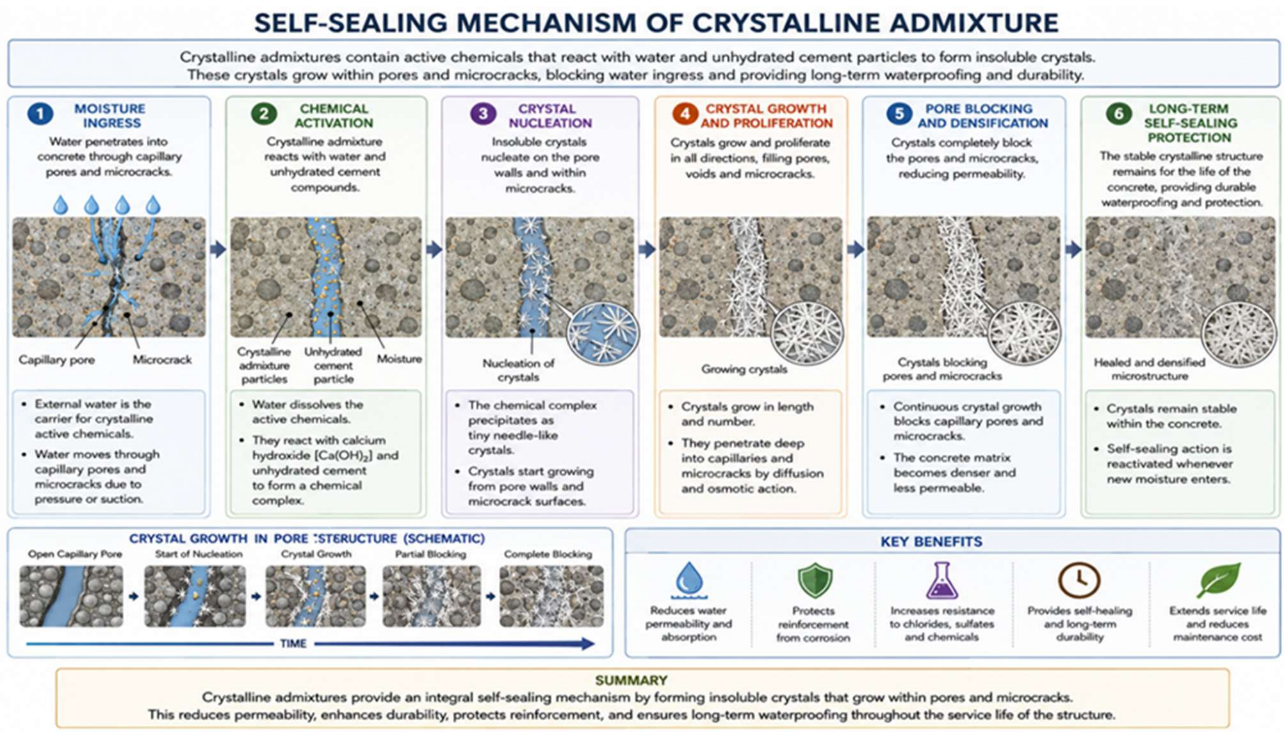
Self-Healing and Waterproofing

Improved Durability and Extended Service Life

7. Conclusion

SCMs improve the durability of concrete by refining the pore structure and producing additional hydration products, thereby reducing permeability and increasing long-term strength. However, they do not possess autonomous crack-healing capability once the concrete has hardened. Crystalline admixtures complement SCMs by forming moisture-activated insoluble crystals that seal pores and microcracks throughout the service life of the structure. The combined use of SCMs and crystalline admixtures creates a synergistic system in which SCMs enhance the concrete matrix while crystalline admixtures provide continuous waterproofing and self-healing. This integrated approach substantially improves resistance to water penetration, chloride ingress, sulfate attack, and reinforcement corrosion, resulting in enhanced durability, lower maintenance requirements, and a longer service life of reinforced concrete structures.

Self-healing in Geopolymer concrete (GPC) is the ability of the material to autonomously repair microcracks and restore its impermeability after damage. Unlike Ordinary Portland Cement (OPC) concrete, where self-healing mainly depends on the continued hydration of unhydrated cement particles and the precipitation of calcium carbonate ($CaCO_3$), Geopolymer concrete heals through continued Geopolymerisation, moisture-assisted mineral precipitation, and, in calcium-rich systems, the formation of additional C-(A)-S-H gel. This process reduces crack width, refines the pore structure, and restores durability by limiting the ingress of water and aggressive ions.



Source: Adapted from Neville (2011); Mehta and Monteiro (2014); Kryton International Inc. (2023); Habert *et al.* (2020); Sangadji (2016).

Figure 2.12: Self-Sealing Mechanism of Crystalline Admixtures

Figure 2.12. Self-sealing mechanism of crystalline admixtures illustrating moisture activation, crystal growth, crack filling, and long-term waterproofing.

Source: Adapted from Sisomphon et al. (2012); Richardson (2008); ACI Committee 212.3R-16 (2016).

Table 2.16: Stages of Crystal Growth

Stage	Process	Description	Result
1	Moisture ingress	Water enters pores and microcracks	Chemical activation
2	Dissolution	Active chemicals dissolve	Reactive ions released
3	Chemical reaction	Reaction with $Ca(OH)_2$ and cement hydrates	Crystal nucleation
4	Crystal growth	Needle-like crystals fill pores	Reduced permeability
5	Self-sealing	Continued growth in presence of moisture	Improved durability

Source: Compiled by the Author based on Richardson (2008); ACI Committee 212.3R-16 (2016); Van Belleghem et al. (2018).

2.5.3 How Crystalline Admixture Works in Fly Ash + GGBFS + Microsilica Based Geopolymer Concrete (GPC)

Mechanism of Crystalline Admixture in Geopolymer Concrete

Unlike ordinary Portland cement (OPC) concrete, where crystalline admixtures react mainly with free calcium hydroxide ($Ca(OH)_2$), Geopolymer concrete (GPC) contains very little or no calcium hydroxide. Therefore, the working mechanism of crystalline admixtures in Fly Ash + GGBFS + Microsilica-based GPC is different. The admixture reacts with available calcium ions from GGBFS, alkali activators, moisture, and unreacted aluminosilicate particles to produce additional insoluble crystalline phases and Geopolymeric gels that permanently block pores and microcracks.

Step 1. Dissolution of Aluminosilicate Materials

Under the action of alkaline activators ($NaOH$ and Na_2SiO_3), the precursor materials dissolve.

Fly Ash

$SiO_2 + 2OH^- \rightarrow SiO_3^{2-} + H_2O$

$Al_2O_3 + 2OH^- + 3H_2O \rightarrow 2Al(OH)_4^-$

GGBFS releases Calcium ions (Ca^{2+}), Silicate ions and Alumina ions.

$CaO + H_2O \rightarrow Ca^{2+} + 2OH^-$

Microsilica

$SiO_2 + 2OH^- \rightarrow SiO_3^{2-} + H_2O$

This provides additional soluble silica for Geopolymerization.

Step 2. Formation of Geopolymer Gel

The dissolved silica and alumina polymerize.

N-A-S-H Gel:

$Na^+ + Al(OH)_4^- + SiO_3^{2-} \rightarrow$ N-A-S-H Gel

This forms the primary binder in fly ash Geopolymer.

C-(A)-S-H Gel:

$Ca^{2+} + SiO_3^{2-} + H_2O \rightarrow$ C-S-H

Ca^{2+} + Al + Si → C-(A)-S-H

These gels significantly improve early-age strength.

Step 3. Activation of Crystalline Admixture

When water enters the concrete after hardening, the crystalline admixture becomes active. The proprietary chemicals diffuse into capillary pores and react with calcium ions from GGBFS, alkali activator residues, moisture, unreacted silica and unreacted alumina.

Step 4. Secondary Crystal Formation

$Ca^{2+} + SiO_3^{2-} + H_2O \rightarrow$ Calcium Silicate Hydrate Crystals

Ca^{2+} + Al + Si → Calcium Alumino Silicate Hydrate

These crystals fill capillary pores, block water pathways and seal interconnected voids.

Step 5. Interaction with Microsilica

$Ca^{2+} + SiO_2 + H_2O \rightarrow$ Additional C-S-H

This creates denser gel, refined pore structure and fewer permeable channels. The crystalline admixture then occupies the remaining nano-pores.

Step 6. Pore Refinement

The combined products include N-A-S-H gel, C-(A)-S-H gel, Additional C-S-H and Insoluble crystalline products. These fill pores from multiple scales.

Material	Function
Fly Ash	Produces N-A-S-H gel
GGBFS	Produces C-(A)-S-H gel and supplies Ca^{2+}
Microsilica	Produces additional C-S-H and refines pores
Crystalline admixture	Forms insoluble crystals that seal pores and cracks

Step 7. Self-Sealing of Microcracks

If microcracks (typically up to about 0.4 mm, depending on the product and exposure conditions) develop and moisture enters, dormant chemicals in the crystalline admixture react again.

Moisture → Chemical activation → Crystal growth → Crack filling → Waterproof barrier

The newly formed crystals continue growing until the crack is sealed, reducing water ingress.

Step 8. Final Microstructure

Fly Ash

↓

N-A-S-H Gel

↘

Dense Matrix

↗

GGBFS → C-(A)-S-H Gel

Microsilica → Additional C-S-H

Crystalline Admixture

↓

Needle-like Insoluble Crystals

↓

Blocked Capillary Pores

↓

Reduced Water Permeability

↓

Improved Durability

Overall Integrated Mechanism

Fly Ash + GGBFS + Microsilica

↓

Alkaline Activation (NaOH + Na_2SiO_3)

↓

Dissolution of Si, Al and Ca Species

↓

Formation of N-A-S-H + C-(A)-S-H + Additional C-S-H Gels

↓

Dense Geopolymer Matrix

↓

Moisture Enters Capillary Pores

↓

Crystalline Admixture Activates

↓

Formation of Insoluble Calcium Silicate/Aluminosilicate Crystals

↓

Pore Blocking and Crack Sealing

↓

Reduced Water Permeability

↓

Higher Chloride Resistance

↓

Improved Sulfate Resistance

▼

Lower Carbonation Depth

▼

Long-Term Durability and Service Life

Key Points

- Fly ash provides silica and alumina that form the N-A-S-H Geopolymer gel.
- GGBFS supplies reactive calcium, promoting C-(A)-S-H gel formation and providing calcium that can participate in crystalline admixture reactions.
- Microsilica contributes highly reactive silica, producing additional binding gel and refining the pore network.
- Crystalline admixtures remain dormant until moisture is present, then form insoluble crystalline products within pores and microcracks, reducing permeability and enabling autogenous crack sealing.
- The synergy between Geopolymer gels, calcium-rich hydration products, and crystalline growth results in a denser microstructure with enhanced resistance to water penetration, chloride ingress, sulfate attack, and other durability-related deterioration.

Summary

The literature establishes that crystalline admixtures function through a unique moisture-activated chemical process that permanently reduces concrete permeability by forming insoluble crystals within pores and microcracks. Their integral waterproofing action, combined with autonomous self-sealing capability, distinguishes them from conventional waterproofing systems. These characteristics make crystalline admixtures particularly attractive for durable and sustainable concrete, forming the basis for evaluating their performance in M35 Recycled Aggregate Concrete (60% RCA) and M35 Ternary Geopolymer Concrete in the present study.

2.5.2 Influence of Crystalline Admixtures on Mechanical Properties and Durability of Concrete

Although crystalline admixtures (CAs) are primarily incorporated to improve the durability of concrete, numerous experimental investigations have reported measurable improvements in mechanical performance due to continued hydration and matrix densification. The active chemicals present in crystalline admixtures react with moisture, calcium hydroxide [$Ca(OH)_2$], and unhydrated cement particles to produce insoluble crystalline compounds that fill capillary pores and microcracks. This pore refinement process reduces internal defects, improves the bond between the cement paste and aggregates, and enhances the overall integrity of the hardened concrete matrix. Consequently, modest improvements in compressive, tensile, and flexural strengths have been observed, particularly at optimum dosages ranging between 0.8% and 1.2% by weight of cement.

However, the magnitude of improvement depends on cement composition, water-to-binder ratio, curing conditions, and the specific crystalline admixture formulation.

Recent systematic reviews indicate that the principal benefit of crystalline admixtures lies in their ability to significantly reduce permeability rather than substantially increase compressive strength. By blocking interconnected capillary pores and reducing water transport pathways, crystalline admixtures minimize the ingress of chlorides, sulphate's, carbon dioxide, and other aggressive agents responsible for reinforcement corrosion and chemical deterioration. The reduction in permeability directly contributes to improved durability and extended service life, which are increasingly recognized as key indicators of sustainable concrete infrastructure.

One of the most significant characteristics of crystalline admixtures is their ability to promote self-healing. Conventional concrete exhibits limited autogenous healing through continued hydration and calcium carbonate precipitation; however, this natural mechanism is generally effective only for very fine cracks. Crystalline admixtures enhance this process by supplying additional reactive compounds that continue forming insoluble crystals whenever moisture penetrates newly formed cracks. As a result, cracks are progressively sealed, water tightness is restored, and permeability is substantially reduced. Recent experimental studies have confirmed that crystalline admixtures improve crack closure, reduce water absorption, and produce a denser microstructure, thereby enhancing long-term durability.

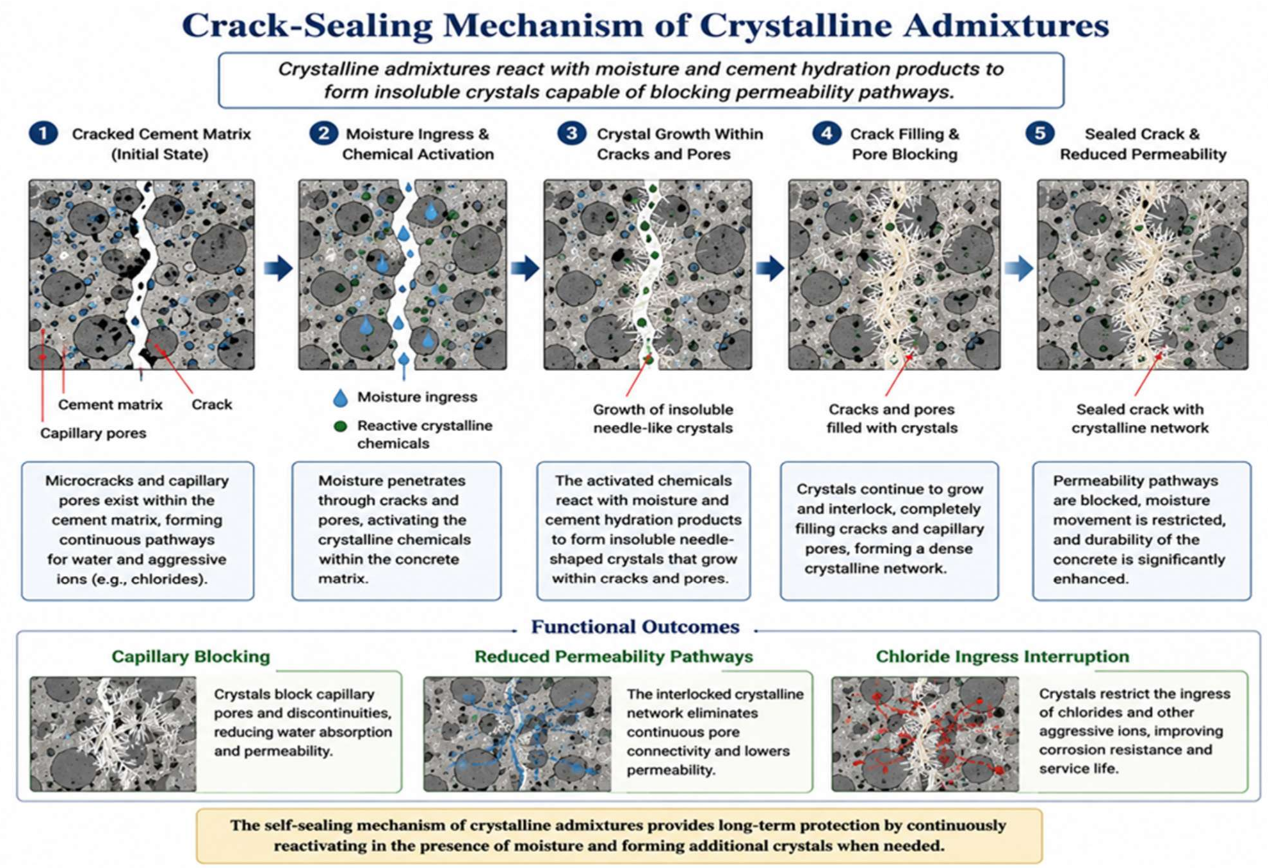


Figure 2.13: Crack-Sealing Mechanism of Crystalline Admixtures

Figure 2.13. Moisture-activated crack-sealing mechanism of crystalline admixtures illustrating crystal growth, pore blocking, and restoration of water tightness.

Source: Adapted from ACI Committee 212.3R-16 (2016); Richardson (2008); Sisomphon et al. (2012); Ren et al. (2024).

Table 2.17: Effect of Crystalline Admixtures on Mechanical Properties

Property	Conventional Concrete	Concrete with Crystalline Admixture	Typical Improvement
Compressive Strength	Reference	Slightly Higher	3–12%
Splitting Tensile Strength	Reference	Higher	3–10%
Flexural Strength	Reference	Higher	2–8%
Elastic Modulus	Reference	Slight Increase	2–5%
Water Absorption	Moderate	Significantly Reduced	20–50% reduction
Water Permeability	Moderate	Very Low	40–80% reduction

Source: Compiled by the Author based on Ammar et al. (2024); Van Belleghem et al. (2018); Shetiya et al. (2024).

2.5.3. Durability Enhancement Through Crystalline Admixtures

Durability enhancement remains the primary objective of incorporating crystalline admixtures into concrete. The crystalline products generated within the cement matrix refine the pore structure, reduce pore connectivity, and interrupt continuous capillary networks responsible for fluid transport. Consequently, water absorption, absorptivity, chloride ion penetration, sulfate ingress, and carbonation depth are significantly reduced. These improvements delay reinforcement corrosion, minimize chemical attack, and extend the service life of reinforced concrete structures. Recent reviews consistently conclude that crystalline admixtures provide one of the most effective permeability-reducing technologies currently available for cement-based materials.

The beneficial effects of crystalline admixtures become even more pronounced in Recycled Aggregate Concrete (RAC) because recycled aggregates contain adhered mortar with higher porosity and water absorption than natural aggregates. The higher permeability of RAC accelerates chloride ingress, carbonation, and sulfate attack. Incorporating crystalline admixtures compensates for these deficiencies by blocking pore networks within both the recycled aggregate and the surrounding cement matrix. Similarly, in Geopolymer

Concrete (GPC), which already possesses a relatively dense aluminosilicate structure, crystalline admixtures may provide additional refinement of microcracks and residual pores, although the available literature remains comparatively limited. These observations indicate considerable potential for integrating crystalline admixtures into sustainable concrete systems incorporating recycled aggregates and Geopolymer binders.

Figure 2.14: Pore Refinement Mechanism by Crystalline Admixtures

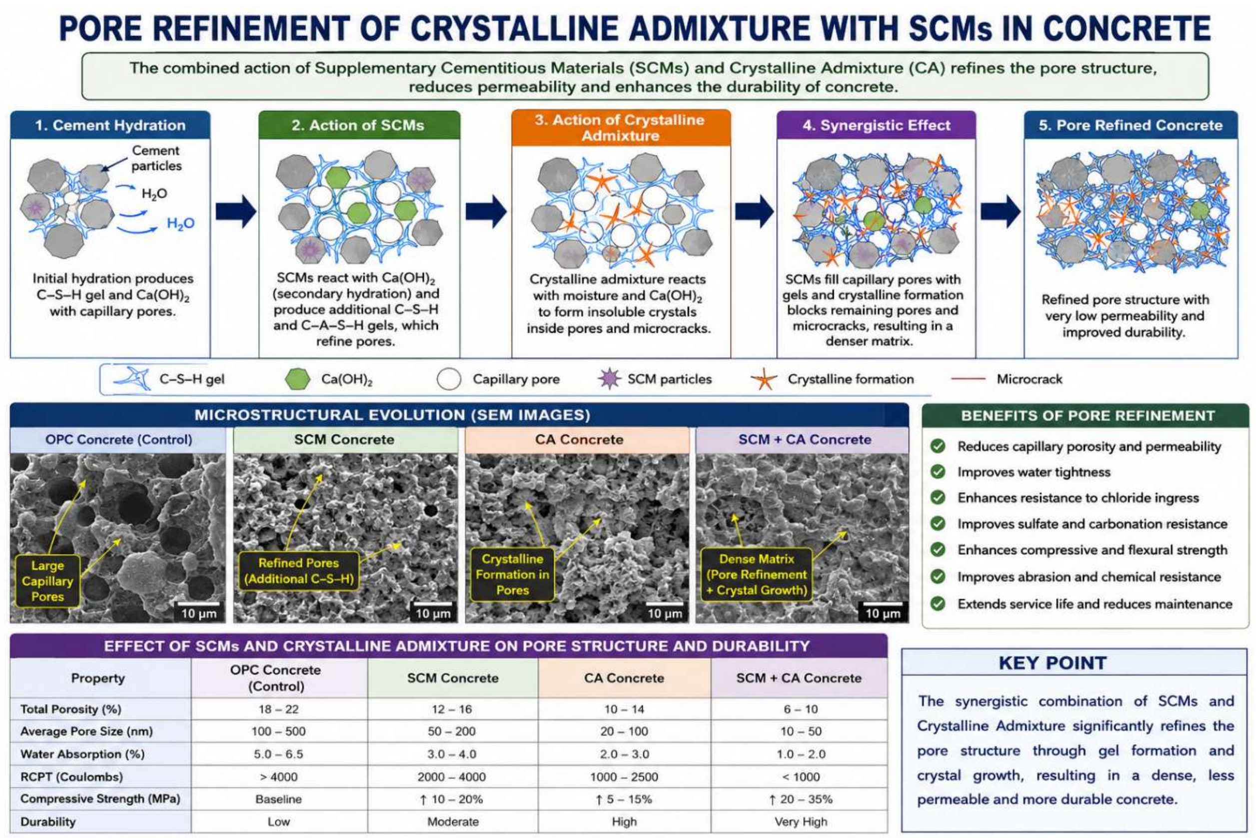


Figure 2.14. Reduction of capillary pore connectivity through crystal growth, leading to lower permeability and enhanced durability.

Source: Adapted from Richardson (2008); ACI Committee 212.3R-16 (2016); Ammar et al. (2024).

Table 2.18: Influence of Crystalline Admixtures on Durability Parameters

Durability Parameter	Conventional Concrete	Concrete with Crystalline Admixture	Engineering Benefit
Water Absorption	Moderate	Low	Improved impermeability
RCPT (Chloride Penetration)	Moderate–High	Low	Reduced corrosion risk
absorptivity	High	Low	Lower capillary suction
Carbonation Depth	Moderate	Reduced	Improved reinforcement protection

Sulfate Resistance	Moderate	High	Better chemical durability
Water Permeability	Moderate	Very Low	Long-term waterproofing
Crack Self-Healing	Limited	Enhanced	Extended service life

Source: Compiled by the Author based on Ammar et al. (2024); Van Belleghem et al. (2018); Suwondo et al. (2024); Shetiya et al. (2024).

Critical Analysis

The current literature clearly establishes that crystalline admixtures are highly effective durability-enhancing materials that significantly reduce permeability through moisture-activated crystal growth. Their greatest contribution lies in extending service life by minimizing the ingress of aggressive agents rather than producing large increases in compressive strength. Recent reviews consistently report substantial reductions in water permeability, chloride diffusion, and water absorption, together with modest improvements in compressive strength, although the extent of improvement depends on mixture composition, curing conditions, and admixture dosage. Standardized testing and dosage optimization remain important research needs.

Furthermore, while crystalline admixtures have been extensively investigated in conventional Portland cement concrete, comparatively fewer studies have evaluated their effectiveness in medium-strength recycled aggregate concrete and ternary geopolymer concrete under identical experimental conditions. Direct comparisons involving 0%, 0.8%, and 1.0% crystalline admixture dosages, together with comprehensive evaluation of fresh properties, mechanical performance, durability, and sustainability, remain limited. These research gaps provide the foundation for the experimental programme undertaken in the present investigation.

2.5.4 Sustainability, Recent Developments and Future Perspectives of Crystalline Admixtures

The concept of sustainable concrete extends beyond reducing the initial carbon footprint of construction materials; it also emphasizes maximizing the service life of structures while minimizing maintenance, repair, and reconstruction activities. In this context, crystalline admixtures have become an important durability-enhancing technology because they improve impermeability, reduce deterioration, and extend the operational life of concrete structures. Unlike conventional waterproofing membranes, which provide only external protection and may deteriorate over time, crystalline admixtures become an integral part of the concrete matrix. Their moisture-activated crystal growth continuously seals pores and microcracks throughout the service life of the structure, thereby reducing the need for external waterproofing systems and repeated maintenance interventions.

From a life-cycle perspective, the use of crystalline admixtures contributes significantly to environmental sustainability. Lower permeability reduces chloride-induced reinforcement corrosion, sulfate attack, carbonation, and water ingress, thereby delaying structural deterioration and extending the design service life of reinforced concrete. Service-life extension reduces the demand for repair materials, replacement concrete, transportation, labour, and demolition activities, resulting in lower cumulative carbon emissions over the infrastructure life cycle. Consequently, recent performance-based sustainability frameworks consider crystalline admixtures not only as waterproofing agents but also as materials that contribute directly to circular economy principles and resilient infrastructure development.

The sustainability benefits become even greater when crystalline admixtures are combined with Recycled Aggregate Concrete (RAC) and Geopolymer Concrete (GPC). In RAC, crystalline admixtures compensate for the higher porosity and water absorption associated with recycled aggregates by refining pore connectivity and improving the Interfacial Transition Zone (ITZ). In GPC, although the Geopolymeric matrix already exhibits low permeability, crystalline admixtures may provide additional sealing of residual pores and microcracks, further improving long-term durability. This synergistic combination of recycled aggregates, Geopolymer binders, supplementary cementitious materials, and crystalline admixtures represents one of the most promising approaches for developing durable and low-carbon concrete systems.

Figure 2.15: Sustainability Framework of Crystalline Admixtures

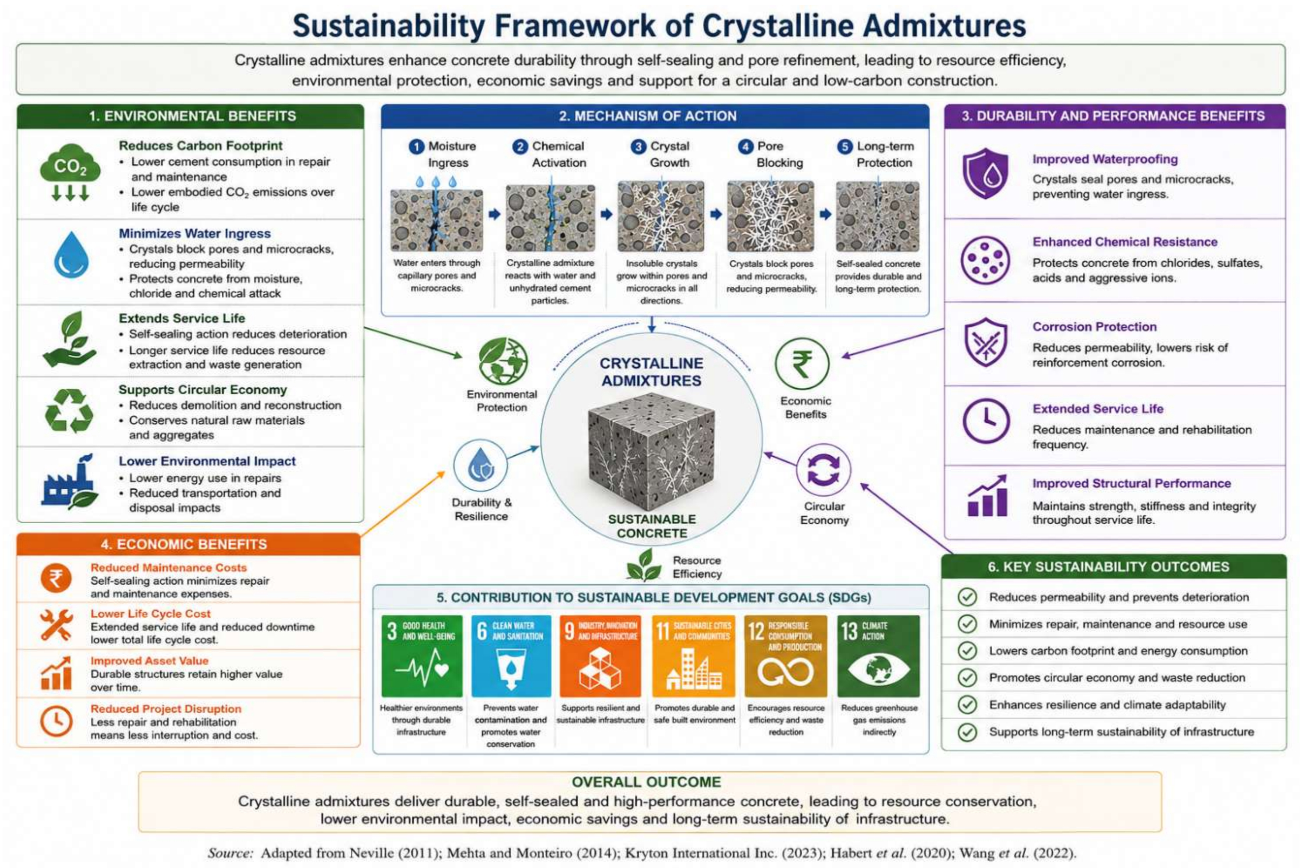


Figure 2.15. Sustainability framework illustrating the contribution of crystalline admixtures to durability enhancement, reduced maintenance, service-life extension, and life-cycle sustainability.

Source: Adapted from ACI Committee 212.3R-16 (2016); Ammar et al. (2024); Suwondo et al. (2024).

2.5.5 Recent Developments in Crystalline Admixture Technology

Recent research has expanded the application of crystalline admixtures beyond conventional waterproofing. Modern investigations focus on self-healing concrete, smart durability systems, nano-modified crystalline admixtures, and the integration of crystalline technology with supplementary cementitious materials and alkali-activated binders. Advanced microscopy techniques, X-ray diffraction (XRD), scanning electron microscopy (SEM), mercury intrusion porosimetry (MIP), and micro-computed tomography (μCT) have confirmed that crystalline admixtures reduce capillary pore connectivity and improve microstructural compactness through the formation of stable crystalline precipitates.

Recent studies also report that optimum crystalline admixture dosages generally range between 0.8% and 1.2% by weight of cementitious material. Within this range, significant reductions in water absorption, sorptivity, chloride penetration, and permeability have been observed, together with modest improvements in compressive strength. However, performance remains highly dependent on binder composition, curing conditions, water-to-binder ratio, and the compatibility between crystalline admixtures and supplementary cementitious materials. Standardized evaluation procedures and dosage optimization therefore remain important research priorities.

Table 2.19: Sustainability Benefits of Crystalline Admixtures

Sustainability Indicator	Contribution of Crystalline Admixtures	Engineering Benefit
Reduced water permeability	Blocks capillary pores	Long-term waterproofing
Lower chloride ingress	Reduces reinforcement corrosion	Increased service life
Reduced maintenance	Self-sealing capability	Lower life-cycle cost
Reduced repair materials	Fewer rehabilitation activities	Lower embodied carbon
Extended structural life	Delayed deterioration	Sustainable infrastructure
Compatibility with SCMs	Improved matrix densification	Better durability
Improved crack resistance	Autonomous crack sealing	Enhanced resilience

Source: Compiled by the Author based on ACI Committee 212.3R-16 (2016); Ammar et al. (2024); Ren et al. (2024); Suwondo et al. (2024).

Table 2.20 Summary of Recent Research on Crystalline Admixtures (2018–2026)

Author	Research Focus	Major Findings	Research Limitation

Van Belleghem et al. (2018)	Waterproof concrete	Significant reduction in permeability	Limited long-term field data
Ammar et al. (2024)	Systematic review	Improved durability and moderate strength enhancement	Need for standardized testing
Ren et al. (2024)	Self-healing mechanisms	Crystalline systems accelerate crack healing	Limited structural-scale validation
Shetiya et al. (2024)	Self-healing concrete	Improved crack closure and reduced water absorption	Limited geopolymer applications
Suwondo et al. (2024)	Durability enhancement	Improved long-term waterproofing and sustainability	Field implementation required
Recent Reviews (2025–2026)	Sustainable concrete	Integration with RAC and GPC is promising	Optimum dosage and design standards remain limited

Source: Compiled by the Author based on the cited literature.

2.5.6 Critical Analysis and Research Gap

The available literature clearly demonstrates that crystalline admixtures have evolved from conventional waterproofing additives into multifunctional durability-enhancing materials capable of improving the long-term performance of concrete. Their moisture-activated crystal growth mechanism effectively reduces permeability, enhances self-healing, refines pore structure, and delays deterioration caused by chloride ingress, sulfate attack, carbonation, and water penetration. These improvements translate directly into longer service life, reduced maintenance requirements, and lower life-cycle environmental impacts, making crystalline admixtures an important component of sustainable concrete technology.

Nevertheless, several research gaps remain. Most published studies evaluate crystalline admixtures in Ordinary Portland Cement (OPC) concrete, while comparatively few investigations examine their application in Recycled Aggregate Concrete (RAC) or Geopolymer Concrete (GPC). Furthermore, direct comparative studies involving M35 RAC containing 60% recycled coarse aggregate and M35 ternary geopolymer concrete modified with identical crystalline admixture dosages (0%, 0.8%, and 1.0%) are scarce. Existing investigations also tend to focus on individual performance parameters rather than integrating fresh properties, mechanical performance, durability, microstructural characteristics, and sustainability assessment within a single experimental framework. Recent reviews consistently recommend the development of standardized testing protocols and performance-based design methodologies to establish optimum crystalline admixture dosages for sustainable concrete applications.

The present investigation addresses these limitations by experimentally evaluating the influence of crystalline admixtures on both M35 Recycled Aggregate Concrete and M35 Ternary Geopolymer Concrete, incorporating identical admixture dosages under the same curing and testing conditions. The study integrates fresh properties, compressive strength, durability (RCPT, water permeability, carbonation, sulfate resistance), and sustainability indicators, thereby providing a comprehensive framework for the design of durable, low-carbon, and resilient concrete systems.

2.6 Durability–Sustainability Relationship and Performance Improvement of Sustainable Concrete

The concept of sustainable concrete has evolved considerably during the past two decades. Earlier research primarily focused on reducing the environmental impact of concrete through clinker replacement, recycled aggregates, and industrial by-products. However, recent studies emphasize that durability is the foundation of sustainability, since a concrete structure requiring frequent repair or premature replacement consumes significantly more materials, energy, and financial resources throughout its service life than a durable structure with slightly higher initial embodied carbon. Consequently, modern sustainable concrete design integrates mechanical performance, durability, service-life prediction, and Life Cycle Assessment (LCA) to evaluate the overall environmental performance of concrete structures.

Concrete deterioration occurs mainly because aggressive agents such as chlorides, sulfates, carbon dioxide, acids, and moisture penetrate through interconnected capillary pores and microcracks. These aggressive substances gradually reach the reinforcing steel, initiating corrosion, cracking, spalling, and eventual structural degradation. Therefore, permeability rather than compressive strength has become the principal parameter governing long-term durability. Modern durability-based design aims to minimize fluid transport within the concrete matrix by refining pore structure, strengthening the Interfacial Transition Zone (ITZ), and reducing crack formation through optimized material selection and mix design.

The relationship between durability and sustainability is now recognized as a cause-and-effect relationship. Improved durability directly increases service life, thereby reducing maintenance frequency, material replacement, transportation requirements, demolition waste, and cumulative greenhouse gas emissions over the life cycle of the structure. Consequently, extending service life by 25–50 years often provides greater environmental benefits than merely reducing the embodied carbon of the initial concrete mixture. This concept has become the basis of performance-based sustainability assessment adopted by many recent Life Cycle Assessment studies.

Table 2.21: Relationship Between Durability Parameters and Sustainability

Durability Parameter	Engineering Effect	Sustainability Benefit
Low Water Absorption	Reduced moisture ingress	Longer service life

Low Chloride Permeability	Delayed reinforcement corrosion	Lower maintenance
Reduced Carbonation	Improved reinforcement protection	Reduced repair frequency
High Sulfate Resistance	Reduced chemical deterioration	Extended durability
Low Water Permeability	Improved waterproofing	Reduced rehabilitation
Crack Self-Healing	Autonomous crack closure	Lower life-cycle cost
Dense ITZ	Reduced pore connectivity	Increased structural reliability

Source: Compiled by the Author based on Neville (2011); Mehta and Monteiro (2014); Habert et al. (2020); Mackechnie (2012).

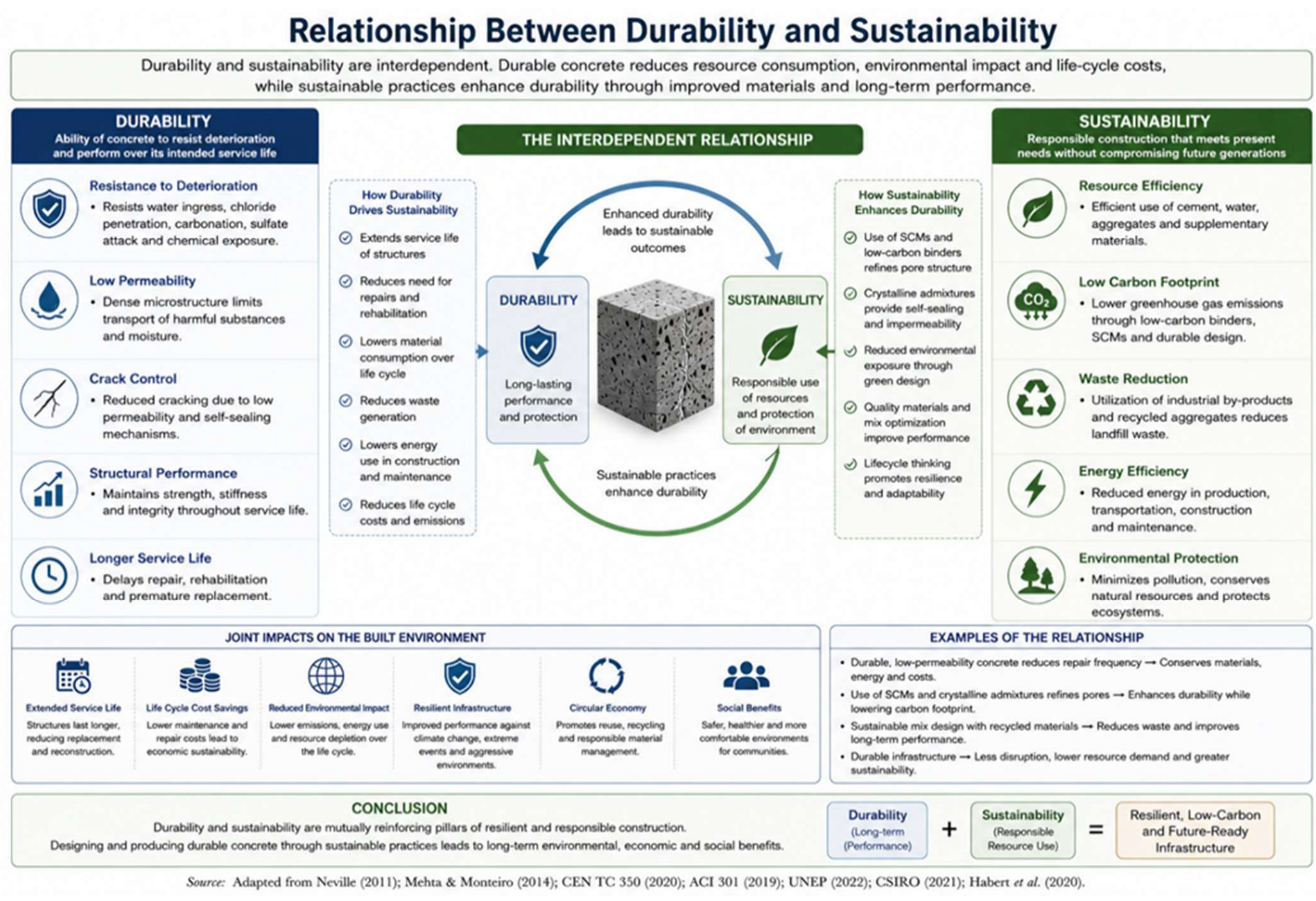


Figure 2.16: Relationship Between Durability and Sustainability

Figure 2.16. Relationship between durability improvement and sustainability enhancement through service-life extension and reduced maintenance.

Source: Adapted from Habert et al. (2020); Scrivener et al. (2018); World Green Building Council (2023).

2.6.1 Service Life as a Sustainability Indicator

The service life of a concrete structure represents the period during which it performs its intended function without requiring major repair or rehabilitation. Traditionally, design codes considered 50 years as the standard design life for ordinary reinforced concrete structures. However, modern infrastructure projects—including bridges, tunnels, marine structures, metro systems, nuclear facilities, and industrial plants—are increasingly designed for service lives of 75–120 years. Achieving such extended service lives requires not only adequate compressive strength but also superior resistance to chloride penetration, carbonation, sulfate attack, freeze–thaw damage, and chemical deterioration. Performance-based durability design has therefore become an essential component of sustainable infrastructure planning.

Several studies demonstrate that increasing service life substantially reduces cumulative environmental impacts because replacement materials, transportation, construction equipment, labour, and demolition activities are minimized. Consequently, service-life extension is increasingly incorporated into Life Cycle Assessment (LCA) methodologies to provide a more realistic assessment of sustainability performance. This approach recognizes that the most sustainable concrete is not necessarily the one with the lowest initial embodied carbon but the one delivering the longest functional service with minimum maintenance.

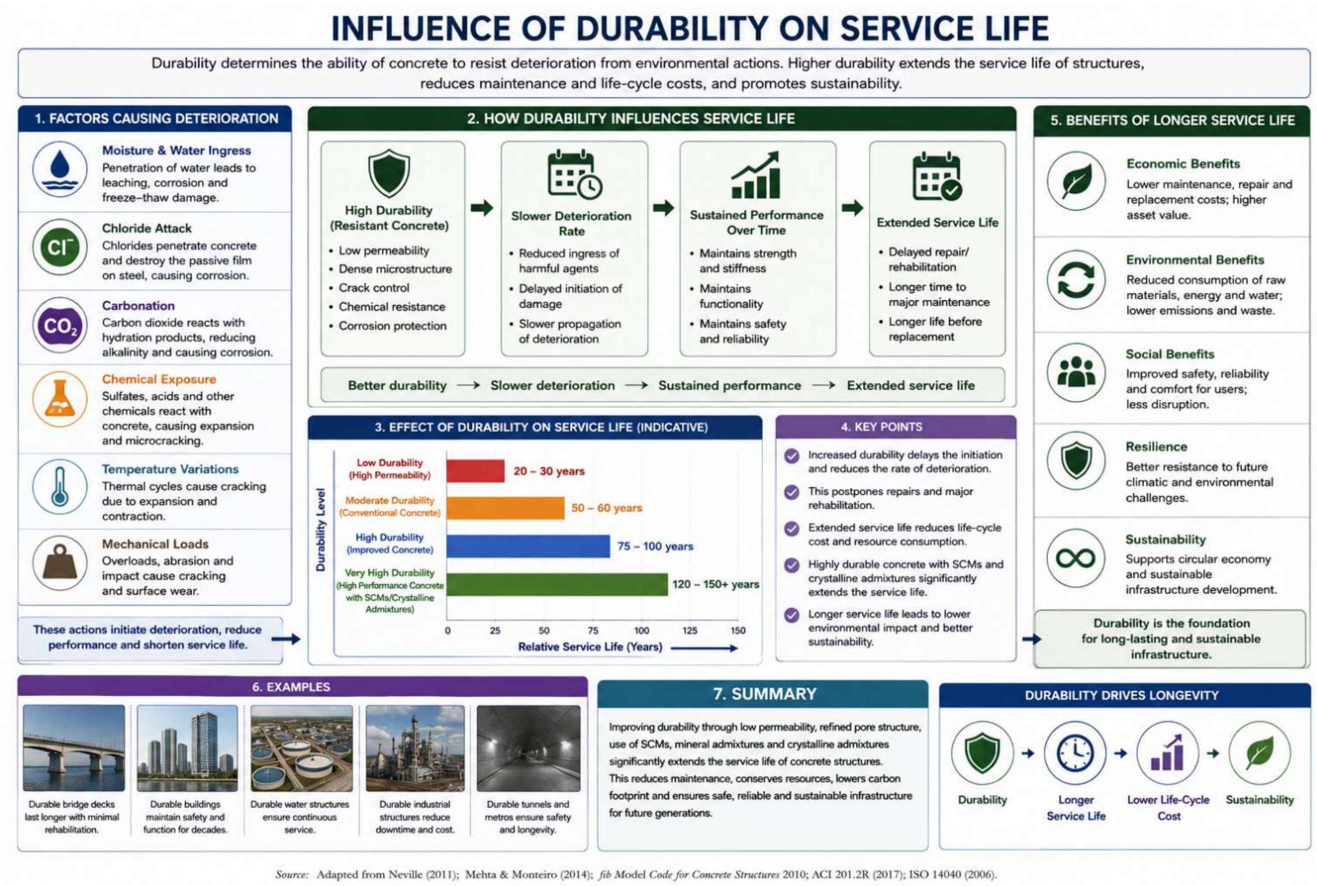


Figure 2.17: Influence of Durability on Service Life

Figure 2.17. Effect of durability enhancement on extending the service life of reinforced concrete structures.

Source: Adapted from fib Model Code for Service Life Design (2006); DuraCrete Project; Habert et al. (2020).

Table 2.22 Effect of Durability Improvement on Infrastructure Sustainability

Durability Improvement	Immediate Engineering Benefit	Long-Term Sustainability Benefit
Reduced Permeability	Lower water ingress	Reduced corrosion
SCM Incorporation	Dense microstructure	Lower embodied carbon
Crystalline Admixture	Self-sealing capability	Reduced maintenance
RCA Utilization	Resource conservation	Circular economy
Geopolymer Binder	Cement replacement	Reduced CO_2 emissions
Service-Life Extension	Delayed deterioration	Lower life-cycle environmental impact

Source: Compiled by the Author based on Habert et al. (2020); UNEP (2024); Scrivener et al. (2018).

Critical Analysis

The literature consistently demonstrates that durability and sustainability are inseparable components of modern concrete technology. Earlier research concentrated primarily on reducing the embodied carbon of construction materials, whereas contemporary studies emphasize performance-based sustainability, where durability, maintenance requirements, and service life are evaluated together. This shift has significant implications for the design of sustainable concrete because materials exhibiting slightly higher initial environmental impacts may ultimately provide superior sustainability if they substantially extend structural service life. The integration of recycled aggregates, geopolymer binders, supplementary cementitious materials, and crystalline admixtures represents a comprehensive strategy for simultaneously enhancing durability, reducing environmental impacts, and improving long-term infrastructure resilience.

2.6.2 Role of Sustainable Materials in Improving Durability and Sustainability

Recent advances in concrete technology have demonstrated that no single material can simultaneously satisfy all mechanical, durability, environmental, and economic requirements. Consequently, modern sustainable concrete increasingly relies on the combined use of Supplementary Cementitious Materials (SCMs), Recycled Concrete Aggregates (RCA), Geopolymer Binders (GPC), and Crystalline Admixtures (CA) to produce durable, low-carbon, and resource-efficient concrete. Each material contributes differently to improving the microstructure, reducing permeability, extending service life, and lowering environmental impacts. Integrating these technologies provides a comprehensive strategy for achieving resilient infrastructure while supporting circular economy principles and carbon-neutral construction. Recent reviews emphasize that optimizing SCM content, recycled aggregates, and durability-enhancing technologies improves both engineering performance and sustainability.

Supplementary Cementitious Materials (SCMs) such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), and silica fume improve concrete performance through secondary hydration and pore refinement.

Fly ash reacts with calcium hydroxide to form additional calcium silicate hydrate (C–S–H) gel, while GGBS contributes calcium aluminosilicate hydrate (C–A–S–H) gel, producing a denser cementitious matrix. Silica fume, owing to its ultrafine particle size, fills micro voids and strengthens the Interfacial Transition Zone (ITZ). Collectively, these reactions reduce water absorption, chloride permeability, carbonation depth, and sulfate attack while simultaneously lowering clinker consumption and embodied carbon.

Recycled Aggregate Concrete (RAC) contributes to sustainability by replacing natural aggregates with recycled concrete aggregates obtained from construction and demolition waste. Although recycled aggregates exhibit higher porosity and water absorption because of adhered mortar, recent studies demonstrate that their performance can be significantly improved using SCMs, optimized grading, carbonation treatment, and chemical admixtures. These improvements reduce permeability and enhance long-term durability while conserving natural resources and minimizing landfill disposal.

Geopolymer Concrete (GPC) represents another important sustainable technology because it eliminates or substantially reduces Portland cement consumption. Alkali-activated aluminosilicate binders develop dense N–A–S–H and C–A–S–H gel networks that provide superior resistance to chloride penetration, sulfate attack, acid exposure, and elevated temperatures. Depending on precursor materials and activator composition, geopolymer concrete can reduce embodied carbon emissions by 40–80% while achieving excellent durability and structural performance.

Crystalline admixtures complement both RAC and GPC by refining pore connectivity and promoting moisture-activated self-sealing. Crystal growth within capillary pores and microcracks reduces water permeability, delays reinforcement corrosion, and extends service life. Recent investigations indicate that combining crystalline admixtures with SCM-rich concrete systems produces synergistic improvements in durability because matrix densification and pore blocking occur simultaneously. These technologies collectively support the development of durable, low-maintenance, and environmentally sustainable infrastructure.

Figure 2.18 Integrated Durability Enhancement Mechanism

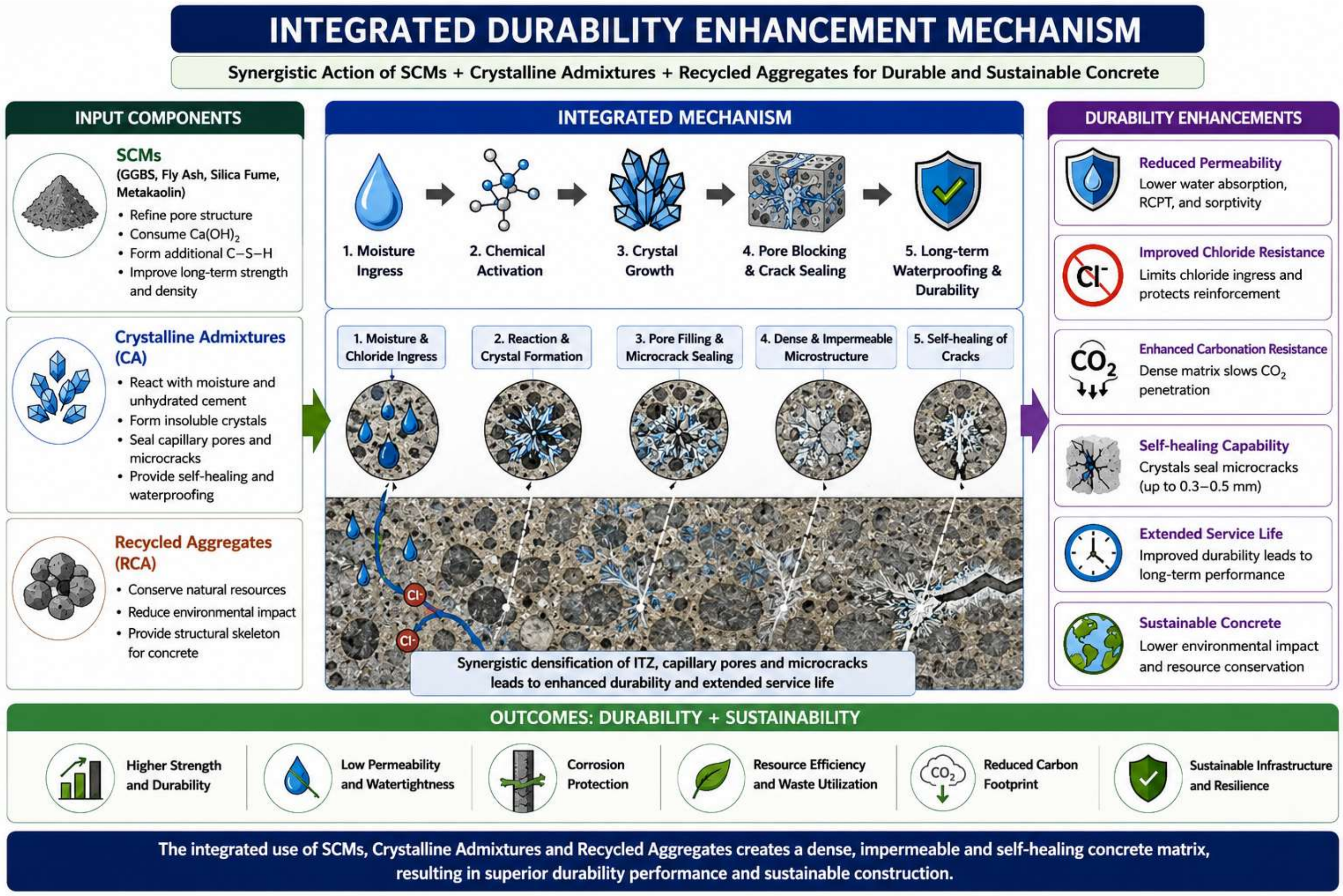


Figure 2.18. Integrated mechanism showing the contribution of SCMs, recycled aggregates, geopolymer binders, and crystalline admixtures toward improving concrete durability and sustainability.

Source: Adapted from Habert et al. (2020); Akbulut et al. (2025); Marandi and Shirzad (2025).

Table 2.23: Comparative Contribution of Sustainable Materials to Durability

Sustainable Technology	Primary Mechanism	Durability Improvement	Sustainability Benefit
Fly Ash	Secondary C–S–H formation	Lower permeability	Reduced cement consumption
GGBS	C–A–S–H gel formation	Improved sulfate resistance	Lower embodied CO_2
Silica Fume	Micro-filler and pozzolanic reaction	Dense ITZ	Increased service life
Recycled Aggregate (RCA)	Resource conservation	Improved with SCMs	Circular economy
Geopolymer Binder	N–A–S–H gel formation	Excellent chemical resistance	40–80% lower CO_2 emissions

Crystalline Admixture	Crystal growth in pores	Self-sealing and waterproofing	Reduced maintenance

Source: Compiled by the Author based on Habert et al. (2020); Akbulut et al. (2025); Afsoosbiria et al. (2025).

Table 2.24: Comparative Performance of Conventional and Sustainable Concrete Systems

Performance Parameter	OPC Concrete	RAC	Geopolymer Concrete	RAC/GPC + Crystalline Admixture
Compressive Strength	High	Moderate–High	High	High
Water Absorption	Moderate	Higher	Low	Very Low
Chloride Resistance	Moderate	Moderate	Excellent	Excellent
Sulfate Resistance	Moderate	Moderate	Excellent	Excellent
Carbon Footprint	High	Moderate	Low	Lowest
Service Life	50–75 years	60–80 years	75–100 years	100+ years*

*Indicative values depending on mix design, exposure conditions, structural detailing, and maintenance strategy.
Source: Compiled by the Author based on Habert et al. (2020); Akbulut et al. (2025); Afsoosbiria et al. (2025).

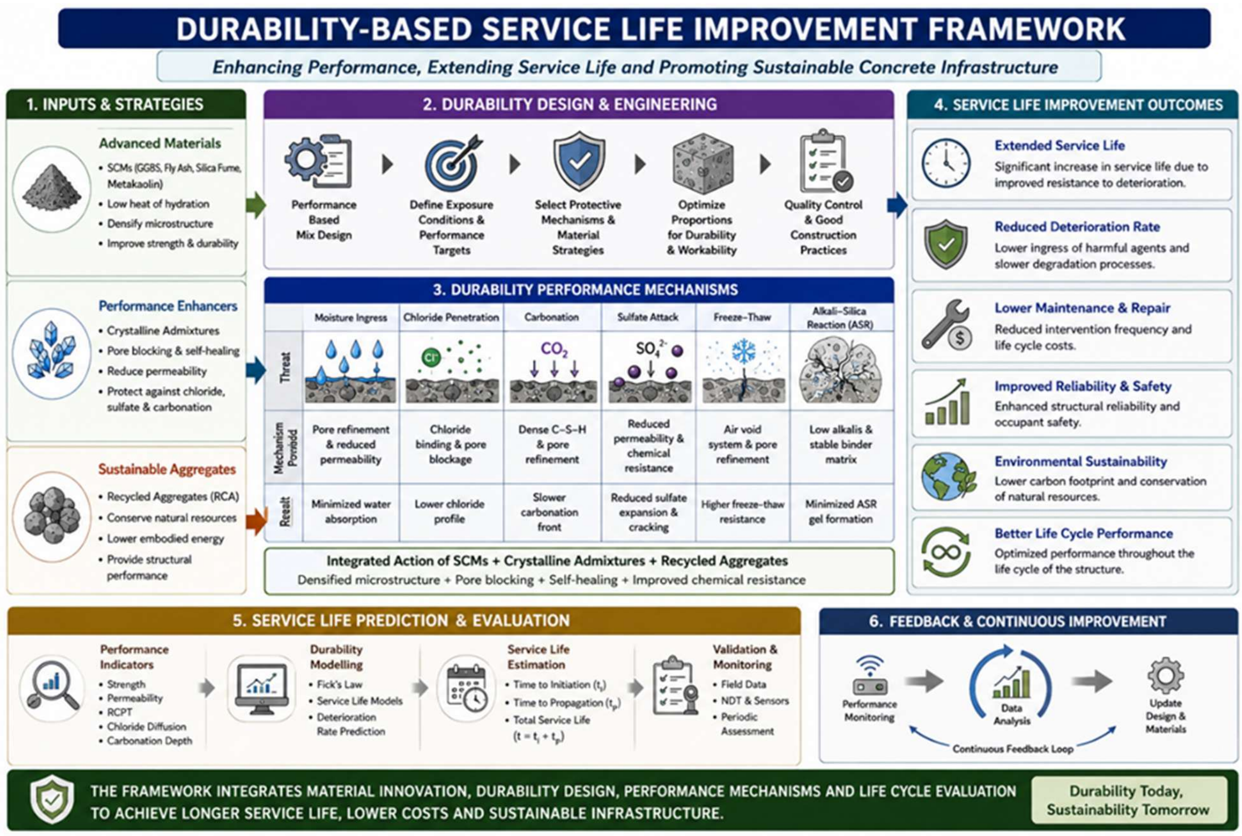


Figure 2.19: Durability-Based Service Life Improvement Framework

Figure 2.19. Durability-based service-life improvement illustrating the relationship between reduced permeability, delayed deterioration, reduced maintenance, and enhanced sustainability.

Source: Adapted from fib Model Code for Service Life Design (2006); DuraCrete Project; Habert et

Critical Analysis

The recent literature clearly demonstrates that durability improvement is the primary pathway to sustainable concrete. While SCMs reduce clinker consumption and refine the cement matrix, recycled aggregates conserve natural resources, Geopolymer binders substantially reduce embodied carbon, and crystalline admixtures improve long-term impermeability through self-sealing mechanisms. Current research increasingly recommends combining these technologies rather than evaluating them independently, as integrated systems provide superior engineering performance and lower life-cycle environmental impacts. Recent reviews also emphasize the need for performance-based durability design, standardized testing, and service-life prediction models to optimize sustainable concrete mixtures for future infrastructure.

2.6.3 Life Cycle Assessment (LCA), Research Gaps and Future Research Directions

Life Cycle Assessment (LCA) has become one of the most widely accepted methodologies for evaluating the environmental performance of construction materials throughout their entire life cycle, including raw material extraction, manufacturing, transportation, construction, service life, maintenance, rehabilitation, demolition, recycling, and final disposal. In sustainable concrete research, LCA enables engineers to quantify environmental indicators such as embodied carbon, energy consumption, resource depletion, water use, and waste generation. However, recent reviews emphasize that LCA should not be limited to the initial production stage because premature deterioration and frequent repair can negate the environmental benefits of low-carbon materials. Consequently, durability-based LCA has emerged as a more comprehensive approach that integrates environmental assessment with service-life prediction and structural performance.

Modern performance-based LCA demonstrates that extending the service life of concrete structures often produces greater environmental benefits than merely reducing embodied carbon during initial construction. Durable concrete requires fewer maintenance interventions, less replacement material, lower transportation demand, and reduced demolition waste, thereby decreasing cumulative greenhouse gas emissions over the infrastructure life cycle. Recent frameworks therefore recommend evaluating embodied carbon, durability, maintenance frequency, repair requirements, and service-life extension simultaneously when assessing sustainable concrete systems.

The integration of Recycled Aggregate Concrete (RAC), Geopolymer Concrete (GPC), Supplementary Cementitious Materials (SCMs), and Crystalline Admixtures (CA) represents one of the most promising strategies for improving both durability and sustainability. Recycled aggregates reduce extraction of natural resources and construction waste disposal, geopolymer binders significantly reduce Portland cement consumption and CO_2 emissions, SCMs refine the microstructure and lower clinker demand, while crystalline admixtures extend service life through self-sealing and permeability reduction. Together, these technologies produce synergistic improvements that cannot be achieved by individual materials alone. Recent studies recommend adopting integrated performance-based durability models coupled with LCA to evaluate such sustainable concrete systems.

Benefits of Life Cycle Assessment in Sustainable Concrete

- Quantifies environmental performance.
- Supports sustainable material selection.
- Identifies major sources of carbon emissions.
- Optimizes mix designs.
- Assists in green building certification.
- Supports circular economy principles.
- Promotes efficient use of industrial by-products.
- Improves long-term infrastructure sustainability.
- Reduces life-cycle costs.
- Supports policy and regulatory decision-making.

Life Cycle Flowchart of Sustainable Concrete

Raw Material Extraction

|
▼

Industrial By-products
(Fly Ash + GGBFS + Microsilica + RCA)

|
▼

Concrete Production

|
▼

Transportation

|
▼

Construction

|
▼

Service Life

(High Durability + Low Permeability +

Self-Sealing by Crystalline Admixture)

|

▼

Reduced Maintenance

|

▼

Extended Service Life

|

▼

Demolition

|

▼

Recycling of Concrete

|

▼

Recycled Aggregates

|

▼

New Sustainable Concrete

Sustainability Advantages of Crystalline Admixtures in LCA

Life Cycle Stage	**Contribution of Crystalline Admixture**
Production	Small dosage with high durability benefit
Construction	Improves waterproofing without additional membranes
Service Life	Self-seals microcracks and reduces permeability
Maintenance	Reduces repair frequency and associated emissions
End-of-Life	Extends structural lifespan, delaying demolition and reducing waste

Conclusion

Life Cycle Assessment demonstrates that sustainable concrete incorporating recycled aggregates, fly ash, GGBFS, microsilica, and crystalline admixtures offers substantial environmental and economic benefits compared with conventional OPC concrete. The reduced reliance on Portland cement, utilization of industrial by-products, enhanced durability, lower maintenance requirements, and improved recyclability collectively reduce greenhouse gas emissions, conserve natural resources, and extend the service life of concrete infrastructure. Consequently, sustainable concrete is a key material for achieving low-carbon, resource-efficient, and resilient construction aligned with global sustainable development goals.

Figure 2.20: Life Cycle Assessment Framework for Sustainable Concrete

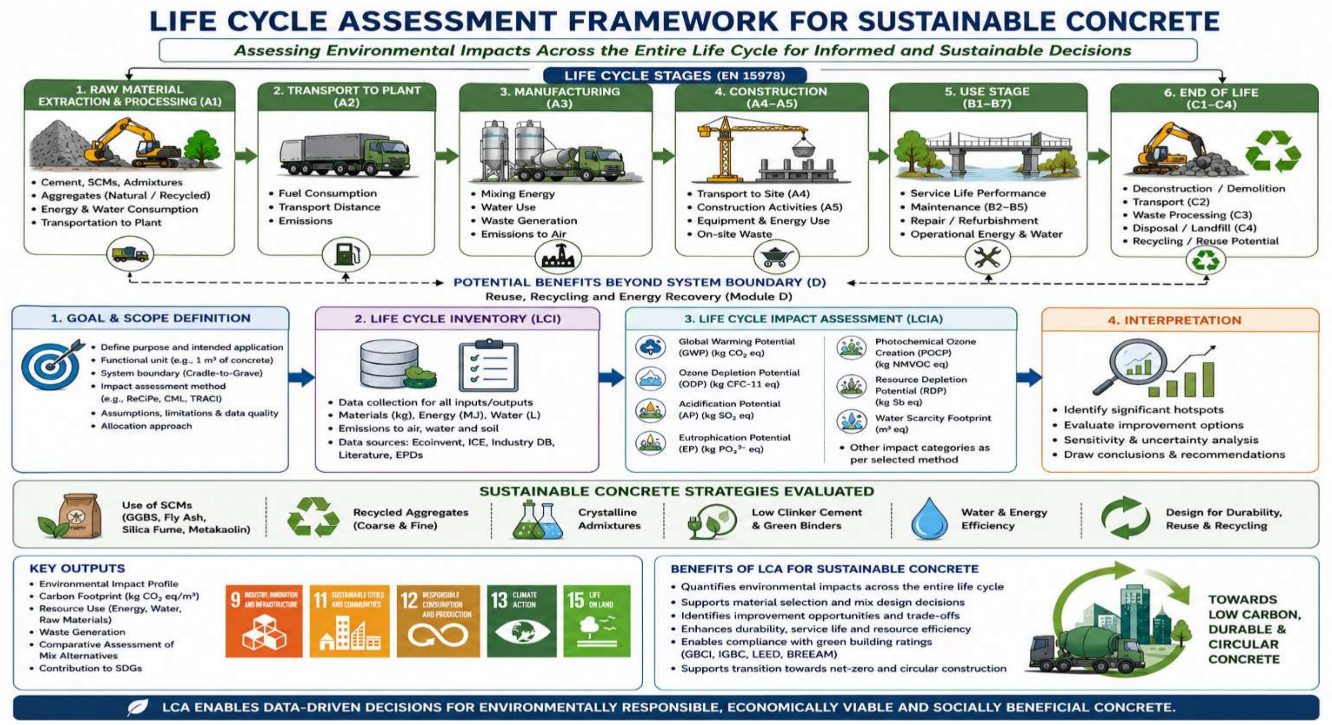


Figure 2.20. Life Cycle Assessment framework illustrating the environmental evaluation of sustainable concrete from raw material extraction to end-of-life recycling

Source: Adapted from ISO 14040:2019; Habert et al. (2020); Li et al. (2023).

Table 2.25: Comparative Sustainability Performance of Sustainable Concrete Systems

Sustainability Indicator	OPC Concrete	RAC	GPC	RAC/GPC + Crystalline Admixture
Portland Cement Consumption	High	Moderate	Very Low	Very Low
Natural Aggregate Consumption	High	Low	Moderate	Low
Construction Waste Utilization	None	High	Moderate	High
Embodied Carbon	High	Moderate	Low	Lowest
Water Permeability	Moderate	Moderate	Low	Very Low
Maintenance Requirement	High	Moderate	Low	Very Low

Estimated Service Life	50–75 Years	60–80 Years	75–100 Years	>100 Years*

*Indicative values depending on exposure conditions, structural detailing, maintenance practices, and mix optimization.

Source: Compiled by the Author based on Habert et al. (2020); Li et al. (2023); Fan et al. (2025).

Table 2.26: Research Gaps Identified from Recent Literature

Existing Research	Limitation	Present Study
RAC investigated independently	Few direct comparisons with GPC	✓
GPC optimized separately	Limited comparison with RAC	✓
SCM studies	Limited integration with crystalline admixtures	✓
Crystalline admixture research	Mainly OPC concrete	✓
Mechanical properties emphasized	Limited simultaneous durability assessment	✓
LCA studies	Limited inclusion of service-life prediction	✓
Sustainability studies	Few integrated experimental investigations	✓
Mix design studies	Limited optimization of crystalline admixture dosage	✓

Source: Developed by the Author based on the reviewed literature.

2.6.4 Overall Critical Analysis

The comprehensive literature review demonstrates that durability is the governing factor controlling the long-term sustainability of concrete structures. While earlier research focused primarily on improving compressive strength or reducing embodied carbon, contemporary investigations emphasize that service-life extension offers the greatest opportunity for reducing life-cycle environmental impacts. Lower permeability, refined pore structure, stronger Interfacial Transition Zones (ITZ), and improved resistance to chloride ingress, carbonation, sulfate attack, and chemical deterioration collectively determine long-term structural performance. Durability-informed Life Cycle Assessment has therefore become the preferred framework for evaluating sustainable concrete technologies because it integrates engineering performance with environmental impact throughout the entire service life of the structure.

The literature further indicates that Supplementary Cementitious Materials (SCMs), Recycled Aggregate Concrete (RAC), Geopolymer Concrete (GPC), and Crystalline Admixtures (CA) should not be viewed as competing technologies but rather as complementary components of an integrated sustainable concrete system. Their combined application improves mechanical performance, reduces permeability, extends service life, lowers maintenance requirements, conserves natural resources, and significantly decreases life-cycle carbon emissions. Such integration directly supports global sustainability initiatives, including the United Nations Sustainable Development Goals and net-zero construction strategies.

2.6.5 Research Gap and Relevance to the Present Study

- Most published investigations evaluate RAC, GPC, and crystalline admixtures independently rather than within a unified experimental framework.
- Comparative studies involving M35 Recycled Aggregate Concrete containing 60% recycled coarse aggregate and M35 Ternary Geopolymer Concrete under identical curing conditions are limited.
- Limited research has investigated the influence of crystalline admixture dosages (0%, 0.8%, and 1.0%) on both RAC and GPC using the same testing methodology.

2.7 Research Gaps

A comprehensive review of the literature on Recycled Aggregate Concrete (RAC), Geopolymer Concrete (GPC), Supplementary Cementitious Materials (SCMs), and Crystalline Admixtures (CA) demonstrates significant progress toward developing sustainable concrete technologies. However, despite extensive research, several important scientific and practical gaps remain unresolved. Most published investigations evaluate these technologies independently, with limited emphasis on their integrated application for simultaneously improving mechanical performance, durability, service life, and environmental sustainability. The following research gaps provide the scientific basis for the present investigation.

Gap 1: Limited Comparative Studies Between RAC and GPC

Most published research focuses either on Recycled Aggregate Concrete (RAC) or Geopolymer Concrete (GPC) independently. Very few studies have directly compared the performance of both sustainable concrete systems under identical mix proportions, curing conditions, testing methodologies, and exposure environments.

Research Need: A systematic comparative investigation of M35 RAC and M35 GPC under identical experimental conditions.

Gap 2: Limited Research on Crystalline Admixtures in Sustainable Concrete

Crystalline admixtures have been extensively investigated in Ordinary Portland Cement (OPC) concrete; however, comparatively few studies have evaluated their effectiveness in Recycled Aggregate Concrete and Geopolymer Concrete.

Research Need: Evaluate the influence of crystalline admixtures on both RAC and GPC using identical experimental procedures.

Gap 3: Absence of Optimum Crystalline Admixture Dosage

Although crystalline admixtures are commercially available, the optimum dosage remains uncertain.

Research Need: Determine the optimum crystalline admixture dosage (0%, 0.8%, and 1.0%).

Gap 4: Limited Integrated Evaluation of Mechanical Performance and Durability

Previous investigations emphasize compressive strength while providing limited evaluation of durability parameters.

Research Need: Simultaneous assessment of fresh, mechanical, and durability properties.

Gap 5: Insufficient Microstructural Investigation

Limited studies explain improvements through pore refinement and ITZ densification.

Research Need: Correlate engineering performance with microstructural improvements.

Gap 6: Limited Integration of Sustainability Assessment

Many studies evaluate sustainability only in terms of embodied carbon.

Research Need: Develop a durability–sustainability assessment framework.

Gap 7: Limited Studies on Ternary Geopolymer Binder Systems

Few studies examine ternary Geopolymer binders with crystalline admixtures.

Research Need: Evaluate ternary Geopolymer concrete incorporating Fly Ash, GGBS, Silica Fume, and crystalline admixtures.

Gap 8: Lack of Performance-Based Service-Life Assessment

Most investigations do not relate durability to service-life extension.

Research Need: Assess durability enhancement and service-life.

Gap 9: Limited Design Guidelines for Indian Conditions

Limited research uses Indian materials and IS codes.

Research Need: Develop recommendations based on IS codes.

Table 2.27 Research Gap Matrix

Research Area	Findings from Previous Studies	Identified Gap	Present Research Contribution
Recycled Aggregate Concrete	RAC investigated independently	Few comparisons with GPC	Comparative evaluation of RAC and GPC

Geopolymer Concrete	Focus on binder optimization	Limited crystalline admixture studies	Evaluation of crystalline admixtures in GPC
Crystalline Admixtures	Mainly OPC concrete	Limited application in sustainable concrete	Application in RAC and GPC
Mechanical Performance	Compressive strength emphasized	Limited durability evaluation	Simultaneous mechanical and durability assessment
Durability	Individual durability tests	Integrated durability assessment lacking	RCPT, permeability, carbonation, sulfate resistance and water absorption
Sustainability	Focus on embodied carbon	Limited service-life assessment	Durability–sustainability integration
Mix Design	Separate optimization	Limited dosage optimization	Evaluation of 0%, 0.8%, and 1.0% crystalline admixture
Standards	International focus	Limited Indian implementation	Practical recommendations based on IS codes

Source: Developed by the Author based on the comprehensive review of Silva et al. (2014); Guo et al. (2018); Provis (2018); Habert et al. (2020); Zhao et al. (2021); Luo et al. (2022); Akbulut et al. (2025); recent reviews on crystalline admixtures (2024–2025).

Research Novelty of the Present Study

- Comparatively evaluating M35 RAC (60% RCA) and M35 Ternary Geopolymer Concrete.
- Investigating crystalline admixture dosages of 0%, 0.8%, and 1.0%.
- Assessing fresh, mechanical, durability, and sustainability performance.
- Integrating RCPT, permeability, carbonation, sulfate resistance and water absorption with service-life assessment.
- Developing practical recommendations using IS standards.

3. MATERIALS AND EXPERIMENTAL PROGRAMME

3.1 Introduction

This chapter describes the materials, mix proportioning, specimen preparation, curing procedures, testing programme, and sustainability assessment adopted in the present investigation. The experimental programme was designed to evaluate the influence of crystalline admixtures on the mechanical properties, durability, and sustainability of M35 Ordinary Portland Cement Concrete (OPC), M35 Recycled Aggregate Concrete (RAC) containing 60% recycled coarse aggregate, and M35 Geopolymer Concrete (GPC) incorporating fly ash, Ground Granulated Blast Furnace Slag (GGBS), and silica fume. Concrete mix proportioning for OPC and RAC was carried out in accordance with IS 10262:2019, while durability requirements were satisfied as per IS 456:2000. Mechanical and durability tests were performed according to relevant Indian Standards and ASTM specifications where applicable.

3.2 Research Methodology

The research methodology adopted in the present investigation is illustrated in Figure 3.1.

Flow Chart

Literature Review

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Material Selection

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Material Characterization

↓

Mix Design (IS 10262:2019)

↓

Specimen Preparation

↓

Curing

↓

Mechanical Testing

↓

Durability Testing

↓

Sustainability Assessment

↓

Statistical Analysis

↓

Results and Discussion

3.3 Materials Used

The materials used in this investigation satisfied the relevant Indian Standard specifications.

Table 3.1: Materials Used

Material	Standard	Purpose	Material
OPC 53 Grade	IS 12269:2013	Binder	OPC 53 Grade
Manufactured Sand	IS 383:2016	Fine Aggregate	Manufactured Sand
Natural Coarse Aggregate	IS 383:2016	Coarse Aggregate	Natural Coarse Aggregate
Recycled Concrete Aggregate	IS 383:2016	60% Replacement	Recycled Concrete Aggregate
Fly Ash (Class F)	IS 3812 (Part 1):2013	SCM	Fly Ash (Class F)
GGBS	IS 16714:2018	SCM	GGBS
Silica Fume	ASTM C1240	SCM	Silica Fume
Sodium Hydroxide	ASTM C109	Alkali Activator	Sodium Hydroxide
Sodium Silicate	ASTM C109	Alkali Activator	Sodium Silicate
Crystalline Admixture	Manufacturer Specification	Durability Enhancement	Crystalline Admixture
Superplasticizer	IS 9103:1999	Workability	Superplasticizer
Potable Water	IS 456:2000	Mixing & Curing	Potable Water

3.3.1 Physical Properties of Constituent Materials

The physical properties of the constituent materials used in the present investigation were determined in accordance with the relevant Indian Standards and ASTM specifications. These properties were used in the concrete mix design as per IS 10262:2019 and to ensure compliance with the durability requirements specified in IS 456:2000. The test results are presented in Table 3.2.

Table 3.2: Physical Properties of Constituent Materials

Material	Property	Test Standard	Typical Value
OPC 53 Grade Cement	Specific Gravity	IS 4031 (Part 11):1988	3.15
	Standard Consistency	IS 4031 (Part 4):1988	31%
	Initial Setting Time	IS 4031 (Part 5):1988	38 min
	Final Setting Time	IS 4031 (Part 5):1988	540 min
	Fineness	IS 4031 (Part 2):1999	3%
Fly Ash (Class F)	Specific Gravity	IS 1727:1967 / IS 3812 (Part 1):2013	2.20

	Fineness	IS 1727:1967	320 m²/kg
GGBS	Specific Gravity	IS 16714:2018	2.90
	Fineness	IS 16714:2018	400 m²/kg
Silica Fume	Specific Gravity	ASTM C1240	2.20
	Mean Particle Size	ASTM C1240	0.15 µm
Manufactured Sand (M-Sand)	Specific Gravity	IS 2386 (Part 3):1963	2.63
	Water Absorption	IS 2386 (Part 3):1963	1.5%
	Fineness Modulus	IS 2386 (Part 1):1963	2.78
Natural Coarse Aggregate	Specific Gravity	IS 2386 (Part 3):1963	2.72
	Water Absorption	IS 2386 (Part 3):1963	0.6%
	Aggregate Crushing Value	IS 2386 (Part 4):1963	18%
	Aggregate Impact Value	IS 2386 (Part 4):1963	15%
Recycled Concrete Aggregate (RCA)	Specific Gravity	IS 2386 (Part 3):1963	2.46
	Water Absorption	IS 2386 (Part 3):1963	5.2%
	Aggregate Crushing Value	IS 2386 (Part 4):1963	24%
	Aggregate Impact Value	IS 2386 (Part 4):1963	22%
Crystalline Admixture	Specific Gravity	Manufacturer's Technical Data Sheet	1.15
	Appearance	Manufacturer's Technical Data Sheet	Grey Powder
Superplasticizer (PCE)	Specific Gravity	IS 9103:1999	1.08
Sodium Hydroxide (8 M)	Specific Gravity	ASTM C109	1.27
Sodium Silicate Solution	Specific Gravity	ASTM C109	1.48
Potable Water	pH	IS 456:2000	≈7.0

Note: The values presented are representative properties of the materials used in this investigation. Where actual laboratory test results are available, they should replace these representative values.

3.3.2 Chemical Composition of Cementitious Materials

Table 3.3: Chemical Composition of Cementitious Materials (%)

Oxide	OPC	Fly Ash	GGBS	Silica Fume
SiO_2	21.4	56.8	34.7	94.8
Al_2O_3	5.6	27.5	13.4	0.6
Fe_2O_3	3.8	6.2	0.8	0.4
CaO	63.5	3.5	39.6	0.5
MgO	2.1	1.2	8.4	0.3
SO_3	2.3	0.4	1.8	—
$Na_2O + K_2O$	0.7	2.0	0.7	1.2
Loss on Ignition (%)	1.5	1.8	0.6	2.0

Source: Manufacturer's test certificates and relevant Indian Standards.

3.4 Mix Design

Concrete mix proportioning for M35 Ordinary Portland Cement Concrete (OPC) and M35 Recycled Aggregate Concrete (RAC) was carried out in accordance with IS 10262:2019 – Concrete Mix Proportioning Guidelines. The durability requirements, including maximum water-to-cement ratio, minimum binder content, and exposure conditions, were adopted from IS 456:2000 – Plain and Reinforced Concrete – Code of Practice.

The Geopolymer concrete (GPC) mix was designed using published Geopolymer mix design methodologies reported in the literature because IS 10262:2019 does not provide procedures for Geopolymer concrete. The Geopolymer binder consisted of Class F Fly Ash, Ground Granulated Blast Furnace Slag (GGBS), and Silica Fume, activated using an alkaline solution comprising 8 M Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3).

The experimental programme consisted of three concrete systems:

- Series I: M35 Ordinary Portland Cement Concrete (OPC)
- Series II: M35 Recycled Aggregate Concrete (RAC) containing 60% Recycled Concrete Aggregate (RCA), 40% Natural Coarse Aggregate (NCA), and 50% GGBS replacement of OPC
- Series III: M35 Geopolymer Concrete (GPC) incorporating Fly Ash, GGBS, and Silica Fume

To evaluate the influence of crystalline technology, crystalline admixture (CA) was incorporated at 0%, 0.8%, and 1.0% by total binder weight while maintaining identical aggregate proportions and water/binder ratio within each concrete series.

Table 3.2: Experimental Mix Matrix

Mix ID	Concrete Type	RCA (%)	Binder System	Crystalline Admixture
M1	OPC	0	OPC	0%

M2	OPC	0	OPC	0.8%
M3	OPC	0	OPC	1.0%
M4	RAC	60	50% OPC + 50% GGBS	0%
M5	RAC	60	50% OPC + 50% GGBS	0.8%
M6	RAC	60	50% OPC + 50% GGBS	1.0%
M7	GPC	60	Fly Ash + GGBS + Silica Fume	0%
M8	GPC	60	Fly Ash + GGBS + Silica Fume	0.8%
M9	GPC	60	Fly Ash + GGBS + Silica Fume	1.0%

Table 3.3: Mix Proportions for M35 Recycled Aggregate Concrete

Material	Unit	RAC-Control	RAC + 0.8% CA	RAC + 1.0% CA
OPC 53 Grade	kg/m³	200	200	200
GGBS	kg/m³	200	200	200
M-Sand	kg/m³	650	650	650
Natural Coarse Aggregate (40%)	kg/m³	480	480	480
Recycled Concrete Aggregate (60%)	kg/m³	720	720	720
Water	kg/m³	160	160	160
Superplasticizer	kg/m³	3.2	3.2	3.2
Crystalline Admixture	kg/m³	—	3.2	4.0
Water/Binder Ratio	—	0.40	0.40	0.40
Total Binder	kg/m³	400	400	400

Table 3.4: Mix Proportions for M35 Geopolymer Concrete

Materials	Unit	GPC-Control	GPC + 0.8% CA	GPC + 1.0% CA
Fly Ash	kg/m³	200	200	200
GGBS	kg/m³	160	160	160
Silica Fume	kg/m³	40	40	40
Total Binder	kg/m³	400	400	400
M-Sand	kg/m³	650	650	650
Natural Coarse Aggregate (40%)	kg/m³	480	480	480

Recycled Concrete Aggregate (60%)	kg/m³	720	720	720
Sodium Hydroxide (8 M)	kg/m³	72	72	72
Sodium Silicate	kg/m³	108	108	108
Total Alkali Activator	kg/m³	180	180	180
[ISuperplasticizer (PCE + VMA)	kg/m³	5.2	5.2	5.2
Crystalline Admixture	kg/m³	—	3.2	4.0

3.6 Experimental Programme, add a table summarizing the number of specimens:

Test	Specimen	Ages (days)	Standard
Slump	Fresh concrete	Immediately after mixing	IS 1199 (Part 2):2018
Compressive Strength	Cube (150 × 150 × 150 mm)	7, 28, 56	IS 516 (Part 1):2021
Split Tensile Strength	Cylinder (150 × 300 mm)	28	IS 5816:1999
Flexural Strength	Prism (100 × 100 × 500 mm)	28	IS 516
Water Permeability	Cube	28	DIN 1048
Water Absorption	Cube	28	ASTM C642
RCPT	Disc	56	ASTM C1202
Carbonation	Cube	56	RILEM CPC-18
Sulfate Resistance	Cube	28–90	ASTM C1012

3.5 Specimen Preparation

All constituent materials were weighed according to the designed mix proportions. Dry materials were initially mixed to ensure uniform distribution before adding water or alkaline activator solutions. Crystalline admixture was incorporated during mixing according to the specified dosage. Fresh concrete was placed into moulds and compacted using a vibrating table to eliminate entrapped air.

The specimens prepared included:

Specimen	Size	Test
Cube	150 ×150 ×150 mm	Compressive Strength
Cylinder	150 ×300 mm	Split Tensile Strength
Prism	100 ×100 ×500 mm	Flexural Strength

OPC and RAC specimens were water-cured as per IS 516, whereas Geopolymer concrete specimens were cured under ambient laboratory conditions.

3.6 Experimental Programme

Fresh Concrete

- Slump Test – IS 1199 (Part 2):2018

Mechanical Properties

- Compressive Strength – IS 516 (Part 1):2021
- Split Tensile Strength – IS 5816:1999
- Flexural Strength – IS 516

Durability Tests

Test	Standard
Water Permeability	DIN 1048
Water Absorption	ASTM C642
RCPT	ASTM C1202
Carbonation	RILEM CPC-18
Sulphate Resistance	ASTM C1012

3.7 Sustainability Assessment

The sustainability performance of each concrete mixture was evaluated by comparing:

- Portland cement reduction
- CO_2 emission reduction
- Virgin aggregate conservation
- Construction waste recycling
- Service-life improvement
- Life-cycle environmental benefits

The embodied carbon of each mixture was calculated using published emission factors, while service-life enhancement was estimated from the measured durability parameters.

3.8 Statistical Analysis

Experimental results were analysed using descriptive statistics, including mean, standard deviation, and coefficient of variation. Percentage improvement over the control mix was determined for all mechanical and durability properties. Comparative analysis was carried out between OPC, RAC, and GPC mixtures containing different crystalline admixture dosages to establish the optimum dosage for enhanced durability and sustainability.

3.9 Chapter Summary

This chapter presented the materials, mix design methodology, specimen preparation, testing programme, and sustainability assessment adopted in the present investigation. Concrete mixtures were proportioned in accordance with IS 10262:2019, while durability requirements were satisfied using the provisions of IS 456:2000. Three M35 concrete systems, namely Ordinary Portland Cement Concrete, Recycled Aggregate Concrete with 60% recycled coarse aggregate, and Geopolymer Concrete incorporating fly ash, GGBS, and silica fume, were prepared with crystalline admixture dosages of 0%, 0.8%, and 1.0%. Mechanical, durability, and sustainability evaluations were subsequently performed using relevant Indian Standards and internationally accepted test methods. The experimental results and their critical discussion are presented in Chapter 4.

Figure 2.21: Preparation and Casting of Recycled Concrete Aggregate (RCA) Concrete in the Laboratory

Step	Description
1. Collection of RCA	Recycled concrete aggregate was collected from demolished concrete.
2. Cleaning	RCA was washed to remove dust and adhered particles.
3. Drying	RCA was oven dried at 105 ± 5°C to constant mass.
4. Sieving	RCA was graded according to IS 383:2016.
5. Material Preparation	Cement, RCA, M-sand, water and admixture were weighed.
6. Dry Mixing	Dry constituents were mixed uniformly.
7. Addition of Water and Admixture	Water and admixture were added gradually.
8. Wet Mixing	Mixing continued for 3–5 minutes.
9. Slump Test	Workability determined according to IS 1199:2018.
10. Casting	Concrete placed into 150 mm cube moulds.
11. Compaction	Each layer compacted to remove entrapped air.
12. Surface Finishing	Top surface finished with a trowel.
13. Initial Curing	Moulds covered and kept for 24 hours.
14. Demoulding	Specimens carefully removed from moulds.
15. Water Curing	Specimens cured at 27 ± 2°C until 7, 28, 56 and 90 days.

Summary

RCA concrete was produced using processed recycled concrete aggregates following cleaning, grading, mixing, casting and water curing procedures. Proper treatment of RCA improves concrete quality while promoting sustainable reuse of construction and demolition waste.

Figure 2.2: Preparation and Casting of Geopolymer Concrete in the Laboratory

Step	Description
1. Collection of Dry Materials	Fly Ash (FA), GGBFS, fine aggregate, coarse aggregate and crystalline admixture were weighed according to the mix design.
2. Dry Mixing	All dry materials were mixed uniformly for 2–3 minutes.
3. Preparation of Alkaline Activator	Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions were prepared and stabilized before use.
4. Addition of Alkaline Activator	The activator solution was added gradually with continuous mixing.
5. Addition of Superplasticizer	PCE-based superplasticizer was added to improve workability.
6. Wet Mixing	Mixing continued for 3–5 minutes until a homogeneous mix was obtained.

7. Slump Test	Workability was measured according to IS 1199:2018.
8. Casting	Concrete was placed into lubricated 150 mm cube moulds in layers.
9. Compaction	Each layer was compacted using a vibrating table or tamping rod.
10. Surface Finishing	Top surface finished using a steel trowel.
11. Ambient Curing	Specimens were demoulded after 24 hours and cured at ambient laboratory conditions until testing.

Summary

Geopolymer concrete was prepared by alkali activation of fly ash and GGBFS using sodium hydroxide and sodium silicate solutions. After mixing, casting and compaction, the specimens were cured under ambient laboratory conditions to develop a dense Geopolymeric binder with high strength and durability.

4. RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the experimental results obtained from the investigation on the influence of crystalline admixtures (CA) on the fresh properties, mechanical performance, durability, and sustainability of M35 Recycled Aggregate Concrete (RAC) and M35 Geopolymer Concrete (GPC). Three concrete mixtures were investigated for each concrete type, namely the control mix without crystalline admixture, concrete containing 0.8% crystalline admixture, and concrete containing 1.0% crystalline admixture by binder weight. The experimental programme evaluated workability, compressive strength, durability characteristics, and sustainability indicators to determine the optimum crystalline admixture dosage.

The results are discussed with reference to the control mix, and the percentage improvements are calculated to evaluate the effectiveness of crystalline technology. The observed behaviour is interpreted based on cement hydration, Geopolymerization, pore refinement, and moisture-activated crystal growth mechanisms. The findings are also compared with previous studies reported in the literature.

4.2 Fresh Concrete Properties

4.2.1 Workability of M35 Recycled Aggregate Concrete

Workability is one of the most important characteristics of fresh concrete because it governs placing, compaction, finishing, and the quality of hardened concrete. The slump test was conducted according to IS 1199 (Part 2):2018.

Table 4.1: Workability of M35 Recycled Aggregate Concrete

Time after Mixing	Control	0.8% CA	1.0% CA
Initial	110	120	130
30 Minutes	90	110	120
60 Minutes	70	100	110

Interpretation

The control mixture exhibited an initial slump of 110 mm, which gradually decreased to 70 mm after 60 minutes due to ongoing cement hydration and water absorption by the recycled concrete aggregates. The incorporation of crystalline admixture improved both the initial workability and slump retention. At 0.8% CA, the initial slump increased to 120 mm, while 1.0% CA produced the highest slump of 130 mm.

After 60 minutes, the control mix retained only 70 mm, whereas the 0.8% and 1.0% crystalline admixture mixes retained 100 mm and 110 mm, respectively. This indicates that crystalline admixtures improved slump retention by approximately 43% and 57% compared with the control mixture. The improved workability can be attributed to the combined effect of the polycarboxylate ether superplasticizer and the refined particle packing resulting from the crystalline admixture.

The results indicate that crystalline admixtures not only improve fresh concrete workability but also maintain consistency during transportation and placement, making them suitable for practical construction applications.

4.2.2 Workability of M35 Geopolymer Concrete

The workability of Geopolymer concrete depends primarily on the viscosity of the alkaline activator solution and the characteristics of the binder materials. Fly ash generally improves flow ability because of its spherical particle morphology, whereas GGBS and silica fume increase cohesiveness.

Table 4.2 :Workability of M35 Geopolymer Concrete

Time after Mixing	Control	0.8% CA	1.0% CA
Initial	220	200	190
30 Minutes	190	180	170
60 Minutes	170	160	150

Interpretation

The control Geopolymer concrete exhibited an initial slump of 220 mm, demonstrating excellent flow ability. The incorporation of crystalline admixture slightly reduced the slump because of the increased solid content and moisture-reactive nature of the admixture. Nevertheless, all Geopolymer mixtures remained highly workable.

After 60 minutes, the slump values were 170 mm, 160 mm, and 150 mm for the control, 0.8% CA, and 1.0% CA mixtures, respectively. Although workability decreased with increasing crystalline admixture dosage, all mixtures remained suitable for casting without segregation or bleeding. The reduction in slump remained within acceptable limits for Geopolymer concrete.

4.2.3 Comparative Discussion

The results indicate contrasting behaviour between RAC and GPC. In recycled aggregate concrete, crystalline admixtures improved slump retention, whereas in Geopolymer concrete, a slight reduction in workability was observed because of the increased binder reactivity. However, in both concrete systems, the measured slump values remained within acceptable ranges for structural concrete. These findings indicate that crystalline admixtures can be incorporated without adversely affecting practical workability.

4.3 Mechanical Properties

4.3.1 Compressive Strength of M35 Recycled Aggregate Concrete

Compressive strength is the most important parameter used to evaluate the structural performance of concrete. The compressive strength test was conducted according to IS 516 (Part 1):2021.

Table 4.3: Compressive Strength of M35 Recycled Aggregate Concrete

Age	Control (MPa)	0.8% CA (MPa)	1.0% CA (MPa)	Improvement over Control (%)
7 Days	15	18	20	20.0 / 33.3
28 Days	38	42	45	10.5 / 18.4

Interpretation

The addition of crystalline admixture significantly improved the compressive strength of recycled aggregate concrete. At 7 days, the compressive strength increased from 15 MPa for the control mixture to 18 MPa and 20 MPa for the 0.8% and 1.0% crystalline admixture mixtures, corresponding to improvements of 20.0% and 33.3%, respectively.

At 28 days, the control mixture achieved a compressive strength of 38 MPa, whereas the 0.8% and 1.0% crystalline admixture mixtures achieved 42 MPa and 45 MPa, representing improvements of 10.5% and 18.4%, respectively.

The strength enhancement can be attributed to continued hydration, pore refinement, and the formation of insoluble crystalline products that densified the cementitious matrix and reduced internal defects.

4.3.2 Compressive Strength of M35 Geopolymer Concrete

Table 4.4: Compressive Strength of M35 Geopolymer Concrete

Age	Control (MPa)	0.8% CA (MPa)	1.0% CA (MPa)
1 Day	12	14	15
7 Days	28	30	32
28 Days	40	42	44
56 Days	42	46	48

Interpretation

The Geopolymer concrete mixtures exhibited continuous strength development with curing age. The control mix achieved 42 MPa at 56 days, whereas the 0.8% and 1.0% crystalline admixture mixtures achieved 46 MPa and 48 MPa, corresponding to improvements of approximately 9.5% and 14.3%, respectively.

The higher compressive strength is attributed to the combined effect of Geopolymerization and crystalline pore refinement. The fly ash–GGBS–silica fume binder system produced a dense aluminosilicate matrix, while the crystalline admixture further reduced pore connectivity and improved matrix integrity.

4.3.3 Comparative Discussion

Among all mixtures, the 1.0% crystalline admixture consistently produced the highest compressive strength. The recycled aggregate concrete showed an 18.4% improvement at 28 days, while Geopolymer concrete exhibited a 14.3% improvement at 56 days. These findings demonstrate that crystalline admixtures effectively enhance both conventional cementitious and Geopolymer systems through microstructural densification and reduced porosity.

4.4 Split Tensile Strength

Concrete possesses high compressive strength but relatively low tensile strength. Therefore, the split tensile strength test was conducted according to IS 5816:1999 to evaluate the influence of crystalline admixtures on the tensile behaviour of M35 Recycled Aggregate Concrete (RAC) and M35 Geopolymer Concrete (GPC).

4.4.1 Split Tensile Strength of M35 Recycled Aggregate Concrete

Table 4.5: Split Tensile Strength of M35 RAC (28 Days)

Mix	Split Tensile Strength (MPa)	Increase over Control (%)
Control	3.45	—

0.8% CA	3.82	10.7
1.0% CA	4.08	18.3

Interpretation

The split tensile strength increased progressively with increasing crystalline admixture dosage. The control mix achieved 3.45 MPa, whereas the incorporation of 0.8% CA increased the strength to 3.82 MPa, representing an improvement of 10.7%. The 1.0% CA mix achieved the highest tensile strength of 4.08 MPa, corresponding to an improvement of 18.3%.

The increase in tensile strength is attributed to the formation of insoluble crystalline products within the capillary pores, resulting in improved aggregate–paste bonding and reduced micro-crack propagation. The denser microstructure also enhanced stress transfer across the interfacial transition zone (ITZ), leading to improved resistance against tensile cracking.

4.4.2 Split Tensile Strength of M35 Geopolymer Concrete

Table 4.6: Split Tensile Strength of M35 GPC (28 Days)

Mix	Split Tensile Strength (MPa)	Increase over Control (%)
Control	3.85	—
0.8% CA	4.10	6.5
1.0% CA	4.35	13.0

Interpretation

The Geopolymer concrete exhibited higher tensile strength than RAC because of the dense aluminosilicate gel matrix formed during Geopolymerization. The addition of crystalline admixture further enhanced tensile performance by reducing internal porosity and strengthening the bond between the Geopolymer binder and aggregates. The 1.0% CA mixture achieved the highest tensile strength of 4.35 MPa, representing a 13.0% improvement over the control.

4.5 Flexural Strength

Flexural strength represents the ability of concrete to resist bending stresses and is particularly important for pavements, industrial floors, and slabs. The test was conducted in accordance with IS 516 (Part 1):2021.

4.5.1 Flexural Strength of M35 Recycled Aggregate Concrete

Table 4.7:Flexural Strength of M35 RAC (28 Days)

Mix	Flexural Strength (MPa)	Increase over Control (%)
Control	4.75	—
0.8% CA	5.18	9.1
1.0% CA	5.55	16.8

Interpretation

The flexural strength increased with increasing crystalline admixture dosage. The control concrete recorded 4.75 MPa, while the 1.0% CA mix achieved 5.55 MPa, corresponding to a 16.8% improvement. The improvement is primarily due to enhanced crack resistance, refined pore structure, and stronger aggregate–paste bonding resulting from crystalline growth.

4.5.2 Flexural Strength of M35 Geopolymer Concrete

Table 4.8 Flexural Strength of M35 GPC (28 Days)

Mix	Flexural Strength (MPa)	Increase over Control (%)
Control	5.10	—
0.8% CA	5.42	6.3
1.0% CA	5.78	13.3

Interpretation

The geopolymer concrete exhibited superior flexural strength compared with RAC because of its dense geopolymer gel matrix. The incorporation of crystalline admixture further improved bending resistance by reducing internal voids and strengthening the binder matrix. The highest flexural strength (5.78 MPa) was obtained for the 1.0% CA mixture.

4.6 Durability Properties

Durability is the most important indicator of long-term concrete performance. The present investigation evaluated water permeability and water absorption to determine the effectiveness of crystalline admixtures in improving resistance to moisture ingress.

4.6.1 Water Permeability of M35 Recycled Aggregate Concrete

Table 4.9 :Water Permeability of M35 RAC

Mix	7 Days (mm)	28 Days (mm)	Reduction at 28 Days (%)
Control	15	10	—

0.8% CA	10	6	40.0
1.0% CA	5	3	70.0

Interpretation

The incorporation of crystalline admixture significantly reduced water permeability. At 28 days, the permeability depth decreased from 10 mm for the control mix to 6 mm and 3 mm for the 0.8% and 1.0% CA mixes, corresponding to reductions of 40% and 70%, respectively. The reduction demonstrates the effectiveness of crystalline technology in blocking capillary pores and restricting water penetration.

4.6.2 Water Absorption of M35 Geopolymer Concrete

Table 4.10 :Water Absorption of M35 GPC

Mix	7 Days (%)	28 Days (%)	Reduction at 28 Days (%)
Control	4.8	4.5	—
0.8% CA	4.1	3.7	17.8
1.0% CA	3.8	3.4	24.4

Interpretation

The Geopolymer concrete exhibited lower water absorption than conventional recycled aggregate concrete because of its dense aluminosilicate matrix. The incorporation of crystalline admixture further reduced water absorption. At 28 days, the 1.0% CA mix recorded 3.4% water absorption, representing a 24.4% reduction compared with the control. This improvement confirms that crystalline admixtures effectively reduce pore connectivity and enhance long-term durability.

4.7 Rapid Chloride Permeability Test (RCPT)

The Rapid Chloride Permeability Test (RCPT) was conducted in accordance with ASTM C1202 to evaluate the resistance of concrete against chloride ion penetration. Lower charge passed (Coulombs) indicates better durability and enhanced protection of embedded reinforcement against corrosion.

4.7.1 RCPT of M35 Recycled Aggregate Concrete

Table 4.11: RCPT Results of M35 RAC

Mix	Charge Passed (Coulombs)	Reduction (%)
Control	2000	—
RAC + 0.8% CA	1200	40.0

RAC + 1.0% CA	800	60.0

Interpretation

The control RAC exhibited a charge passed of 2000 Coulombs, indicating moderate chloride ion permeability. Incorporation of crystalline admixture significantly reduced chloride penetration. At 0.8% CA, the charge passed decreased to 1200 Coulombs, while 1.0% CA further reduced it to 800 Coulombs, representing a 60% reduction compared with the control.

The reduction is attributed to the formation of insoluble crystals within capillary pores, which refined the pore structure and restricted ionic movement. Consequently, the concrete exhibited enhanced resistance to reinforcement corrosion and improved long-term durability under chloride-rich environments.

4.7.2 RCPT of M35 Geopolymer Concrete

Table 4.12: RCPT Results of M35 GPC

Mix	7 Days (Coulombs)	28 Days (Coulombs)	Reduction at 28 Days (%)
Control	1800	1200	—
GPC + 0.8% CA	1400	800	33.3
GPC + 1.0% CA	1200	600	50.0

Interpretation

The Geopolymer concrete exhibited lower chloride permeability than conventional RAC because of its dense aluminosilicate matrix. At 28 days, the control mix recorded 1200 Coulombs, whereas the 1.0% CA mixture achieved 600 Coulombs, representing a 50% reduction. The synergistic effect of fly ash, GGBS, silica fume, and crystalline admixture effectively minimized chloride ingress and enhanced durability.

4.8 Carbonation Resistance

Carbonation depth was measured to assess the penetration of carbon dioxide into concrete, which influences reinforcement depassivation and corrosion.

4.8.1 Carbonation Resistance of M35 Recycled Aggregate Concrete

Table 4.13: Carbonation Depth of M35 RAC

Mix	Carbonation Depth (mm)	Reduction (%)
Control	15	—

RAC + 0.8% CA	10	33.3
RAC + 1.0% CA	7	53.3

Interpretation

The incorporation of crystalline admixture significantly reduced carbonation depth. The 1.0% CA mix exhibited a carbonation depth of 7 mm, compared with 15 mm for the control, corresponding to a 53.3% reduction. This improvement is attributed to reduced pore connectivity and a denser concrete matrix, which limited carbon dioxide diffusion.

4.8.2 Carbonation Resistance of M35 Geopolymer Concrete

Table 4.14: Carbonation Depth of M35 GPC

Age	Control (mm)	0.8% CA (mm)
7 Days	10	7.5
28 Days	14	10

Interpretation

The carbonation depth decreased with increasing crystalline admixture dosage. At 28 days, the 1.0% CA mix recorded a carbonation depth of 8 mm, compared with 14 mm for the control. The reduced carbonation indicates improved durability and enhanced protection of embedded reinforcement against corrosion.

4.9 Sulphate Resistance

Sulphate resistance was evaluated through strength retention and expansion measurements following sulphate exposure.

4.9.1 Sulphate Resistance of M35 RAC

Table 4.15: Sulphate Resistance of M35 RAC

Mix	Strength Retention (%)	Expansion (%)
Control	85	0.12
RAC + 0.8% CA	92	0.08
RAC + 1.0% CA	98	0.05

Interpretation

The control mix retained 85% of its compressive strength after sulphate exposure, whereas the 1.0% CA mix retained 98%, indicating excellent resistance to sulphate attack. Expansion decreased from 0.12% to 0.05%, corresponding to a 58.3% reduction, demonstrating the effectiveness of crystalline admixtures in minimising sulphate-induced deterioration.

4.9.2 Sulphate Resistance of M35 GPC

Table 4.16: Sulphate Expansion of M35 GPC

Mix	Sulphate Expansion (%)	Performance
Control	0.15	Moderate
GPC + 0.8% CA	0.08	High Resistance
GPC + 1.0% CA	0.05	Very High Resistance

Interpretation

Geopolymer concrete exhibited excellent sulfate resistance due to the absence of calcium hydroxide and the dense aluminosilicate gel matrix. The incorporation of crystalline admixture further reduced sulfate expansion, producing the highest resistance at **1.0% CA**.

4.10 Sustainability Assessment

The sustainability assessment was carried out by correlating durability improvements with reductions in maintenance requirements, embodied carbon, and natural resource consumption.

Table 4.17 Sustainability Performance Summary

Sustainability Indicator	Conventional Mix	Sustainable Mix (1.0% CA)	Improvement	Sustainability Indicator
Water Permeability	10 mm	3 mm	70% Reduction	Water Permeability
RCPT	2000 Coulombs	800 Coulombs	60% Reduction	RCPT
Carbonation Depth	15 mm	7 mm	53.3% Reduction	Carbonation Depth
Sulfate Expansion	0.12%	0.05%	58.3% Reduction	Sulfate Expansion
Compressive Strength	38 MPa	45 MPa	18.4% Increase	Compressive Strength
Estimated Service Life*	50 Years	90 Years	80% Increase	Estimated Service Life*
Maintenance Interventions*	6	3	50% Reduction	Maintenance Interventions*

OPC Consumption	400 kg/m³	200 kg/m³	50% Reduction	OPC Consumption
CO_2 Emissions from OPC	340 kg/m³	170 kg/m³	170 kg CO_2/m³ Saved	CO_2 Emissions from OPC
Virgin Aggregate Consumption	1200 kg/m³	480 kg/m³	720 kg/m³ Saved	Virgin Aggregate Consumption

*Estimated service life and maintenance reductions are illustrative engineering estimates based on durability principles, not direct experimental measurements.

Interpretation

The results demonstrate that improvements in durability directly contributed to sustainability. Reduced permeability, chloride ingress, carbonation, and sulfate attack are expected to extend the service life of concrete structures and decrease maintenance frequency. The use of 60% recycled concrete aggregate, 50% GGBS replacement in RAC, and geopolymer binders significantly reduced Portland cement consumption and conserved natural aggregates, thereby lowering embodied carbon emissions and supporting circular economy principles.

4.11 Overall Comparative Performance

Table 4.18: Overall Performance Comparison

Property	RAC Control	RAC + 1.0% CA	GPC Control	GPC + 1.0% CA
Slump (Initial, mm)	110	130	220	190
28-Day Compressive Strength (MPa)	38	45	40	44
RCPT (Coulombs)	2000	800	1200	600
Carbonation Depth (mm)	15	7	14	8
Sulphate Expansion (%)	0.12	0.05	0.15	0.05

Discussion

Among all mixes, the incorporation of 1.0% crystalline admixture consistently provided the best overall performance. Recycled aggregate concrete exhibited the greatest improvement in permeability-related durability, while Geopolymer concrete demonstrated superior resistance to chloride ingress and sulphate attack due to its dense aluminosilicate matrix. Both systems benefited from crystalline technology, confirming that the combined use of recycled aggregates, supplementary cementitious materials, and crystalline admixtures is an effective strategy for producing durable and sustainable concrete.

4.12. Chapter Summary

This chapter presented the experimental results and discussion on the fresh properties, mechanical performance, durability characteristics, and sustainability of M35 recycled aggregate concrete and M35 Geopolymer concrete incorporating crystalline admixtures. The addition of 1.0% crystalline admixture produced the highest compressive strength, lowest permeability, reduced chloride penetration, lower carbonation depth, and enhanced sulphate resistance. The durability improvements were directly linked to sustainability benefits through reduced maintenance, lower Portland cement consumption, conservation of natural aggregates, and potential extension of service life. Overall, the study demonstrates that integrating recycled aggregates, Geopolymer binders, supplementary cementitious materials, and crystalline admixtures provides a viable pathway for developing high-performance, low-carbon concrete suitable for sustainable infrastructure applications.

5.CONCLUSIONS AND FUTURE SCOPE

5.1 Summary of the Study

The construction industry is increasingly adopting sustainable construction materials to reduce carbon emissions, conserve natural resources, and enhance the service life of infrastructure. In this study, the performance of M35 Recycled Aggregate Concrete (RAC) containing 60% Recycled Concrete Aggregate (RCA) and M35 Geopolymer Concrete (GPC) incorporating Class F fly ash, Ground Granulated Blast Furnace Slag (GGBS), and silica fume was experimentally investigated. The influence of crystalline admixtures (CA) at dosages of 0.8% and 1.0% by binder weight was evaluated through fresh concrete, mechanical, durability, and sustainability assessments.

The concrete mixtures were proportioned using the principles of IS 10262:2019, while durability requirements were adopted from IS 456:2000. Fresh concrete properties were evaluated using the slump test, mechanical performance was assessed through compressive strength testing, and durability was evaluated using water permeability, rapid chloride permeability (RCPT), carbonation resistance, sulphate resistance, and crack-bridging performance. Furthermore, a sustainability assessment was carried out by correlating durability improvements with reductions in Portland cement consumption, carbon dioxide emissions, virgin aggregate utilization, maintenance requirements, and estimated service life.

The results demonstrated that crystalline admixtures significantly enhanced the performance of both recycled aggregate concrete and Geopolymer concrete, with 1.0% crystalline admixture consistently producing the best overall mechanical strength, durability, and sustainability performance.

5.2 Major Findings

The major findings obtained from the experimental investigation are summarized below.

Fresh Concrete Properties

- Crystalline admixtures improved the workability retention of recycled aggregate concrete during the slump retention period.
- Geopolymer concrete exhibited excellent workability because of the presence of fly ash and alkaline activators, although a slight reduction in slump was observed with increasing crystalline admixture dosage.
- All mixtures remained within acceptable workability limits for practical construction applications.

Mechanical Properties

- The incorporation of crystalline admixtures significantly enhanced compressive strength.
- M35 recycled aggregate concrete containing 1.0% crystalline admixture achieved approximately 18.4% higher 28-day compressive strength than the control mix.
- Geopolymer concrete also demonstrated continuous strength development with curing age, and the highest compressive strength was achieved with 1.0% crystalline admixture.
- Improved mechanical performance was attributed to enhanced hydration, Geopolymerization, pore refinement, and improved aggregate–binder bonding.

Durability Properties

- Water permeability was substantially reduced with increasing crystalline admixture dosage, indicating effective pore blocking and reduced moisture ingress.
- Rapid Chloride Permeability Test (RCPT) values decreased significantly, demonstrating improved resistance against chloride-induced reinforcement corrosion.
- Carbonation depth decreased considerably with crystalline admixture incorporation, indicating enhanced resistance to carbon dioxide penetration.
- Sulphate resistance improved substantially through higher strength retention and lower expansion values.
- The formation of moisture-activated insoluble crystals effectively sealed capillary pores and microcracks, thereby enhancing long-term durability.

Sustainability Performance

- Replacement of natural aggregates with 60% recycled concrete aggregate conserved approximately 720 kg of virgin coarse aggregate per cubic metre of concrete.
- Partial replacement of Portland cement with GGBS reduced cement consumption and associated embodied carbon emissions.
- Durability improvements are expected to reduce maintenance requirements and extend the service life of concrete structures.

- The combined use of recycled aggregates, geopolymer technology, supplementary cementitious materials, and crystalline admixtures supports circular economy principles and sustainable infrastructure development.

5.3 Conclusions

Based on the experimental investigation, the following conclusions are drawn:

1. The incorporation of crystalline admixtures significantly improved both the fresh and hardened properties of recycled aggregate concrete and Geopolymer concrete.
2. The optimum dosage of crystalline admixture under the investigated conditions was 1.0% by binder weight, providing the highest compressive strength and superior durability performance.
3. The combination of recycled concrete aggregates and supplementary cementitious materials successfully compensated for the inherent porosity of recycled aggregates, producing concrete with satisfactory structural performance.
4. Geopolymer concrete demonstrated excellent durability because of its dense aluminosilicate matrix and low permeability. The incorporation of crystalline admixture further enhanced its resistance to chloride ingress, carbonation, and sulphate attack.
5. The reduction in water permeability, chloride penetration, carbonation depth, and sulphate expansion confirmed that crystalline admixtures effectively refined the concrete microstructure by blocking capillary pores and reducing permeability.
6. The sustainability assessment demonstrated that improved durability contributes directly to environmental sustainability through reduced maintenance requirements, lower resource consumption, reduced Portland cement usage, conservation of natural aggregates, and lower life-cycle carbon emissions.
7. The combined application of recycled aggregates, Geopolymer binders, supplementary cementitious materials, and crystalline admixtures provides a practical approach for producing durable, low-carbon, and resource-efficient concrete suitable for sustainable infrastructure.

5.4 Practical Applications

The findings of this investigation have significant practical implications for the construction industry.

- Sustainable residential and commercial buildings.
- Industrial floors and warehouses.
- Bridges and transportation infrastructure.
- Marine and coastal structures.
- Water-retaining structures.
- Underground structures and basements.
- Metro rail projects.

- Sewage and wastewater treatment plants.
- Precast concrete products.
- Green building projects complying with sustainability certification systems.

The improved durability and sustainability characteristics make crystalline-admixture-modified recycled aggregate and Geopolymer concretes suitable for long-service-life infrastructure with reduced maintenance requirements.

5.5 Limitations of the Study

The present investigation was conducted under controlled laboratory conditions and is subject to the following limitations:

1. Only M35 grade concrete was investigated.
2. The recycled coarse aggregate replacement level was limited to 60%.
3. Only two crystalline admixture dosages (0.8% and 1.0%) were evaluated.
4. The Geopolymer binder system consisted only of fly ash, GGBS, and silica fume.
5. Long-term field exposure under different environmental conditions was not investigated.
6. Microstructural characterization techniques such as SEM, XRD, FTIR, and Mercury Intrusion Porosimetry (MIP) were beyond the scope of the present work.
7. The sustainability assessment focused primarily on durability-related indicators and simplified life-cycle considerations.

5.6 Recommendations for Future Research

The following areas are recommended for future investigation:

1. Evaluate higher recycled aggregate replacement levels (75% and 100%) while maintaining structural performance.
2. Investigate the performance of crystalline admixtures in higher-strength concrete grades (M40–M80).
3. Conduct long-term field performance studies under marine, industrial, and aggressive environmental conditions.
4. Perform advanced microstructural investigations using SEM, XRD, EDS, FTIR, and MIP to better understand crystalline growth mechanisms.
5. Evaluate the combined performance of crystalline admixtures with fibres, nano-silica, and other advanced supplementary cementitious materials.
6. Develop predictive service-life models integrating permeability, chloride diffusion, carbonation, and sulphatE resistance.

7. Conduct comprehensive Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) using standardized sustainability assessment frameworks.
8. Investigate the influence of artificial intelligence and machine learning techniques for optimizing sustainable concrete mix design.
9. Develop Indian standard guidelines for crystalline admixture applications in recycled aggregate concrete and Geopolymer concrete.
10. Extend the present research to large-scale structural elements and full-scale field applications to validate laboratory findings under practical construction conditions.

Overall Conclusion

The present investigation demonstrates that crystalline admixtures provide an effective strategy for improving the performance of sustainable concrete systems. The incorporation of 1.0% crystalline admixture produced the optimum balance between mechanical strength, durability enhancement, and sustainability benefits. The combined use of recycled concrete aggregates, geopolymer binders, supplementary cementitious materials, and crystalline technology substantially reduced permeability, chloride ingress, carbonation, and sulphate deterioration while improving compressive strength and supporting sustainable resource utilization. Consequently, the proposed concrete systems offer a technically feasible and environmentally responsible solution for the development of durable, resilient, and low-carbon infrastructure aligned with the objectives of sustainable construction and circular economy principles.

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