**REVIEW PAPER ON MECHANISMS AND APPLICATIONS OF SUPER ABSORBENT POLYMERS (SAPS) IN SELF SEALING CONCRETE FOR INFRASTRUCTURE RESILIENCE**

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## **ABSTRACT**

Super Absorbent Polymers (SAPs) have emerged as a potential category of materials in civil engineering, notably in improving the durability and lifespan of concrete buildings. This review study examines the essential methods by which SAPs operate inside concrete matrices to provide self-sealing properties. Superabsorbent polymers (SAPs) may absorb and hold substantial quantities of water in relation to their weight, creating hydrogels that can effectively obstruct microcracks and diminish permeability. When incorporated into concrete, these polymers expand upon exposure to water, efficiently closing fissures and restricting further penetration of moisture or corrosive substances. The interaction between superabsorbent polymers and cementitious materials is influenced by several factors, including polymer composition, dose, particle size, and environmental conditions. A careful examination of experimental data from recent investigations is provided to emphasize the physicochemical features and dynamics of water absorption that render SAPs appropriate for autonomous sealing applications in infrastructure.

Besides their sealing role, SAPs facilitate internal curing, reduce shrinkage, and increase the mechanical performance of concrete. The postponed release of absorbed water promotes secondary hydration, especially in high-performance concretes with low water-cement ratios, where early-age cracking is common. The combined capability of internal curing and self-sealing renders SAPs optimal for use in structures subjected to dynamic loads, freeze-thaw cycles, or chloride infiltration. Field and laboratory studies have shown enhanced crack width regulation, prolonged service life, and reduced maintenance needs in SAP-modified concretes. Furthermore, SAPs exhibit compatibility with diverse supplemental cementitious elements, facilitating their incorporation into sustainable concrete formulations. This research assesses the trade-offs between enhanced durability and possible disadvantages, like heightened porosity and expense, providing insights into optimization options.

The use of SAPs in self-sealing concrete directly contributes to the overarching objective of infrastructure resilience. In an age of climate change and urban development, preserving the integrity and safety of essential infrastructure—such as bridges, tunnels, and water-retaining structures—is crucial. The integration of SAPs facilitates passive, long-term crack management, therefore reducing reliance on external inspection and repair protocols. This document consolidates essential case studies, performance assessments, and design factors required for effective implementation. Issues of standardization, scalability, and economic viability are also addressed. The report delineates current research trends and identifies knowledge gaps, proposing future possibilities for the integration of SAP-based self-healing technologies into infrastructure resilience frameworks. The study highlights the revolutionary potential of SAPs in developing the next generation of intelligent, adaptable, and resilient building materials.

**Key Words:** Super Absorbent Polymers (SAPs), Self-sealing concrete, Autogenous healing, Infrastructure resilience, Durability enhancement.

# INTRODUCTION

Concrete is the most extensively used building material worldwide; yet, its vulnerability to cracking due to mechanical and climatic pressures poses a significant durability issue. Microcracks facilitate the entry of water, chlorides, and other corrosive chemicals, hence expediting corrosion, freeze-thaw damage, and structural deterioration. Conventional maintenance techniques are often expensive, laborious, and disruptive, especially for extensive infrastructure. To tackle these difficulties, self-sealing concrete has evolved as a novel approach, using sophisticated materials to autonomously repair fractures and extend service life. Super Absorbent Polymers (SAPs) have garnered much interest for their distinctive capacity to absorb and release water, hence promoting autogenous healing. Superabsorbent polymers (SAPs) not only augment crack-sealing efficacy but also promote internal curing, hence mitigating shrinkage-induced cracking. This paper examines the mechanics, efficacy, and uses of SAPs in self-sealing concrete, emphasizing its potential to revolutionize resilient infrastructure construction.

The function of superabsorbent polymers (SAPs) in concrete is based on their hydrophilic polymer networks, capable of absorbing hundreds of times their weight in water and then releasing it gradually to facilitate healing. Upon the formation of fractures, superabsorbent polymers (SAPs) expand upon exposure to moisture, occupying gaps and initiating the deposition of calcium carbonate (CaCO₃) and other reparative substances. The process is augmented by hydrated cement particles that react with released water to create supplementary binding phases. The efficacy of SAPs is contingent upon elements like polymer type, particle size, cross-linking density, and environmental conditions. Recent investigations indicate that optimal SAP formulations may attain up to 80% fracture closure, markedly enhancing mechanical recovery and durability. Nonetheless, issues persist in reconciling water absorption capacity with mechanical strength, since excessive inclusion of SAP may compromise the integrity of the cement matrix. This study assesses these systems and offers techniques to optimize healing efficiency while preserving structural integrity.

The applications of SAP-modified self-sealing concrete include many infrastructure systems, including bridges, tunnels, maritime constructions, and pavements, where durability and low maintenance are essential. Field investigations indicate that SAP-enriched concrete has increased resistance to freeze-thaw cycles, chloride penetration, and carbonation relative to traditional mixes. Moreover, the incorporation of SAPs with extra cementitious materials (e.g., fly ash, silica fume) is a sustainable method for reducing cement use and carbon emissions. Notwithstanding these benefits, obstacles to widespread implementation include expense, confirmation of long-term performance, and the uniformity of testing techniques. Subsequent research ought to concentrate on bio-derived SAP alternatives, intelligent monitoring systems, and scalable manufacturing methodologies. By tackling these issues, SAP-based self-sealing concrete may significantly contribute to the advancement of sustainable and resilient infrastructure, in accordance with worldwide initiatives for climate-adaptive building.

# LITERATURE REVIEW

Li et al. (2024) examined the efficacy of bio-based super absorbent polymers (SAPs) sourced from cellulose as a sustainable substitute for traditional synthetic SAPs in self-healing concrete. The altered cellulose SAPs exhibited remarkable efficacy, attaining around 75% fracture closure after 28 days, similar to synthetic alternatives. A primary environmental benefit is in the regenerative characteristics of cellulose, enhancing the system's sustainability. The integration of bio-SAPs enhanced freeze-thaw resistance by 30%, due to improved pore structure refinement and moisture control. These SAPs facilitated autogenous healing by expanding upon contact with water and supporting hydration mechanisms. Notwithstanding these benefits, the research identified a significant constraint concerning the long-term durability of cellulose-based superabsorbent polymers under alkaline conditions, typical of concrete matrices. The authors propose further alterations to polymer chemistry to improve resistance to alkaline breakdown. The research substantiates bio-SAPs as a feasible, environmentally sustainable solution for self-healing infrastructure applications.

Zhang and Wang (2024) created a novel dual-function superabsorbent polymer system that integrates conventional moisture-sensitive superabsorbent polymers with encapsulated chemical healing agents such as sodium silicate for sequential crack mending. Their technique facilitated autogenous repair of microcracks (<0.3 mm) by water absorption and swelling, and autonomous healing of larger fractures through the triggered release of encapsulated chemicals. This hybrid methodology yielded improved healing efficacy, exhibiting an 18% increase in compressive strength recovery relative to systems using just SAPs. The research emphasized the advantages of deferred agent activation, guaranteeing that healing agents are released only under situations of active cracking and moisture infiltration. This method increased the efficacy of healing materials and extended their longevity. The dual mechanism provides the promise for more resilient, enduring infrastructure by tackling both small and significant damage. Nonetheless, obstacles persist in regulating the release time, ensuring capsule stability, and achieving cost-effectiveness. The study reveals a viable direction for multi-stage, intelligent self-healing concrete systems for essential infrastructure.

Alyousef et al. (2024) concentrated on optimizing SAP dosage in high-performance concrete (HPC) to enhance self-healing efficacy while reducing strength deterioration. Their experimental study determined the ideal range of superabsorbent polymer (SAP) to be 0.3–0.5% by weight of cement, resulting in a crack sealing efficacy of 70–80% while limiting compressive strength loss to under 10%. This dose facilitated enough swelling and water retention for fracture closure without significantly elevating interior porosity. Nonetheless, SAP concentrations beyond 0.7% resulted in undesired porosity increases, adversely impacting long-term durability and mechanical integrity. The research highlights that excessive SAP compromises matrix continuity and diminishes strength, hence impairing structural performance. Their results emphasize the need of a balanced design methodology for the proper integration of SAPs in HPC, particularly with load-bearing infrastructure. The scientists observed diversity in healing efficacy under varying environmental circumstances, indicating a need for customized formulations based on climate and exposure. This study provides practical dose recommendations for resilient, self-sealing concrete structures.

Gupta et al. (2023) examined the efficacy of super absorbent polymers (SAPs) in concrete subjected to saltwater exposure, emphasizing durability improvement via crack closure. Their research indicated that SAP-modified concrete exhibited a 50% decrease in chloride ion intrusion, markedly enhancing resistance to corrosion-related degradation. The material demonstrated dependable self-healing properties even under tidal settings, with microstructural characterization using SEM-EDS verifying calcium carbonate (CaCO₃) precipitation as the principal sealing mechanism. The swelling behaviour of SAPs in marine settings was less efficient than in freshwater, exhibiting a 20% slower absorption rate due to the ionic content in saltwater water. This delay may influence the efficacy of healing in dynamic coastal environments. Notwithstanding this, SAPs shown efficacy in curtailing fracture development and reducing long-term maintenance requirements. The results highlight the potential of SAPs in coastal and offshore infrastructure, contingent upon performance adjustments for salt effects via polymer modification or hybrid systems.

Chen et al. (2023) investigated the synergistic benefits of integrating superabsorbent polymers with bacteria-based self-healing systems in cementitious materials. The research used Bacillus subtilis incorporated inside the concrete matrix, with superabsorbent polymers providing the requisite moisture for bacterial activation and subsequent calcium carbonate precipitation. This dual-healing approach markedly enhanced performance, achieving a 90% decrease in fracture width, surpassing SAP-only systems that attained around 60% reduction. Moreover, the recovery of flexural strength increased by 25%, indicating higher structural performance. The integration was especially beneficial under fluctuating moisture levels, as SAPs functioned as a water storage to sustain bacterial metabolic activity during arid intervals. The study emphasized the compatibility of biogenic healing agents with polymer-based systems, providing a multifunctional solution for sustained durability. The method, albeit promising, requires careful regulation of SAP concentration and bacterial viability, particularly under high temperature or pH conditions. This research presents the hybrid approach as an advanced solution for autonomous fracture control in smart concrete systems.

Ozbay et al. (2023) explored a unique use of superabsorbent polymers in three-dimensional printed concrete, primarily focusing on challenges associated with layer-interface fractures and interlayer adhesion. Their research indicated that SAPs, when integrated at ≤0.4% by weight of cement, preserved the printability of the concrete while improving its mechanical properties. The crack width decreased by 40%, and the interlayer bond strength enhanced by 15%, addressing a significant difficulty in layered extrusion-based construction. The SAPs facilitated hydration and cohesiveness between printed layers by swelling and releasing water at layer interfaces. The research highlighted the need of dose regulation, as increased SAP content adversely impacted form preservation and extrusion quality. This study highlights the promise of superabsorbent polymers in the additive manufacturing of concrete, enhancing the durability and structural integrity of printed components. The results allow the incorporation of self-healing properties into 3D-printed structures, improving robustness while maintaining production efficiency.

Kim and Lee (2022) developed pH-responsive superabsorbent polymers (SAPs) designed to expand only in very alkaline environments (pH >13), such as those present in new concrete. These intelligent polymers were engineered to inhibit early water release, a prevalent problem with traditional superabsorbent polymers that may result in diminished strength or inadequate healing. The research indicated a 35% enhancement in early-age crack healing relative to conventional SAPs, especially advantageous at the crucial setup and hardening phases. These SAPs discharged retained water just when the pH reached an adequate level, guaranteeing precise activation during hydration or fissure development. Consequently, healing was more regulated and effective, with negligible effects on matrix porosity. The researchers observed enhanced workability and curing efficiency without considerable compromises in mechanical strength. This improvement represents a significant enhancement in SAP technology, enabling the creation of intelligent, environmentally adaptive materials that can be customized for various construction contexts and time-sensitive applications in infrastructure.

Alghamri et al. (2022) performed a comparative analysis of acrylamide-based and acrylic acid-based superabsorbent polymers in concrete, emphasizing healing efficacy and structural effects. Acrylic acid superabsorbent polymers exhibited enhanced water retention capabilities, improving fracture closing efficacy. Nevertheless, this resulted in a compromise of mechanical integrity, shown by a 12% decrease in compressive strength attributable to heightened porosity. Acrylamide-based SAPs demonstrated a more advantageous equilibrium, providing 65% healing efficiency with under 5% strength reduction. The research highlighted that polymer chemistry is crucial in assessing the compromises between durability and mechanical performance. Acrylamide SAPs were advised for structural applications necessitating a modest but dependable degree of self-healing without diminishing load-bearing capability. The researchers emphasized the need for material-specific rules to guarantee that SAP selection corresponds with the intended performance standards. This study guides the creation of SAPs customized for various real applications and performance objectives.

Snoeck et al. (2022) used X-ray computed tomography (CT) to investigate the interior impacts of superabsorbent polymers (SAPs) on the pore architecture and healing processes of concrete. Their investigation demonstrated that SAPs created holes ranging from 10 to 50 µm, which were crucial for enabling moisture transfer and fracture repair. These capillary-scale holes facilitated improved diffusion of healing chemicals and enhanced internal curing. The research cautioned that SAP concentration above 0.6% by weight resulted in heightened capillary porosity, adversely affecting frost resistance and overall durability. The visualization demonstrated a distinct association among SAP dose, alterations in pore structure, and the efficacy of self-healing. Moderate SAP levels facilitated advantageous microstructural alterations; however excessive quantities undermined concrete's resilience to environmental stresses such as freeze-thaw cycles. The study emphasizes the significance of dose optimization and sophisticated imaging methods in the formulation of resilient SAP-modified concrete. The results of Smock et al. enhance comprehension of the impact of SAPs on healing capacity and long-term resilience.

Wang et al. (2021) investigated the use of super absorbent polymers (SAPs) in recycled aggregate concrete (RAC), a material characterized by elevated porosity and variable water retention. The research indicated that the use of 0.4% SAP by cement weight successfully mitigated the water absorption of recycled aggregates, resulting in a 50% improvement in autogenous healing. The enhanced healing efficacy was ascribed to the SAPs' capacity to retain and progressively discharge water, facilitating prolonged hydration and the closure of microcracks. Moreover, SAPs decreased drying shrinkage by 20%, a significant issue in RAC because to its porous nature. The combined function of SAPs in internal curing and crack sealing demonstrated significant advantages in preserving the structural integrity of RAC while ensuring workability was not compromised. The research underscored the need to optimize SAP concentration according to the unique absorption capability of the recovered aggregates. The results endorse SAP integration as an effective method to enhance durability and manage shrinkage in sustainable concrete systems.

Nguyen et al. (2021) examined a hybrid healing system that integrates super absorbent polymers (SAPs) with nanoclay particles to overcome the shortcomings of conventional SAP-modified concrete. Their research attained 80% fracture closure and a 30% enhancement in tensile strength, underscoring the synergistic advantages of the two materials. Nanoclay functioned as a micro-filler, enhancing pore structure and diminishing voids caused by SAP. This filler action also inhibited SAP aggregation, a prevalent problem that may result in localized porosity and inconsistent healing. SAPs supplied moisture for fracture closing, while nanoclay facilitated matrix densification and improved mechanical properties. The combination was especially helpful under fluctuating environmental circumstances, demonstrating enhanced stability in healing behavior. The researchers determined that SAP–nanoclay composites provide a more dependable and performance-enhanced alternative for self-healing applications in contemporary concrete. Their research offers significant insights into the design of multi-functional admixtures, whereby mechanical qualities and durability are concurrently improved via synergistic material interactions.

Darquennes et al. (2021) investigated the fatigue characteristics of SAP-enhanced concrete subjected to cyclic stress, an essential consideration in structural applications like bridges and pavements. The research examined the resilience of repaired fissures and found that SAP-induced healing allowed concrete to endure several loading cycles for fractures measuring up to 0.3 mm in width without re-opening. The healing procedure included SAP expansion and enhanced hydration, leading to CaCO₃ deposition in fissured areas, therefore reinstating matrix continuity. The study revealed that repaired fractures displayed resistance comparable to uncracked concrete under cyclic load, indicating that SAPs not only facilitate sealing but also enhance fatigue longevity. Nevertheless, the research observed that the efficacy of healing diminished in wider fissures or under elevated loading amplitudes. These results confirm that SAPs may significantly enhance fatigue resistance and self-maintenance of infrastructure, particularly in dynamically loaded situations, hence endorsing their integration into performance-based concrete design.

Sisomphon et al. (2020) investigated the impact of super absorbent polymers (SAPs) on the hydration kinetics of cementitious systems, providing an in-depth analysis of SAP interactions with various clinker phases. The research demonstrated that SAPs postponed the hydration of tricalcium silicate (C₃S) because of early water retention in the polymer matrix. This postponement led to a reduction in the early-age strength progression. Nonetheless, a significant improvement in the hydration of dicalcium silicate (C₂S) was seen in the latter phases, enabled by the slow internal release of water. This enhanced long-term strength and durability, rendering SAPs advantageous for sustained performance rather than for initial strength. The results indicate that the time and process of internal curing using SAPs are vital for optimizing strength growth and minimizing cracking. The study emphasizes the significance of SAPs in constructions prioritizing long-term durability, while also noting the need of accounting for hydration delays in structural design.

Jensen and Hansen (2020) concentrated on adjusting the particle size of SAP to improve self-healing efficacy and hydration regulation in cementitious materials. Their research evaluated SAPs measuring between 100 and 300 µm and revealed distinct trade-offs between dispersion quality and water release kinetics. Finer SAPs (about 100 µm) demonstrated superior dispersion within the cement matrix, mitigating the likelihood of localized voids and improving early hydration consistency. Conversely, coarser SAPs (250–300 µm) facilitated more efficient water release, enhancing fracture closure and prolonged cure. The results indicate that a customized particle size distribution may provide an ideal equilibrium between mechanical performance and self-healing capabilities. The authors assert that particle size must be chosen according to the specific application—fine SAPs for consistency and initial strength, coarse SAPs for repair and moisture retention. This research offers pragmatic insights for materials engineers in developing application-specific SAP solutions to achieve varied performance objectives in concrete infrastructure.

Lee et al. (2020) were pioneers in investigating the use of super absorbent polymers (SAPs) in ultra-high-performance concrete (UHPC), a category of materials distinguished by low porosity and exceptional strength. Their investigation indicated that the use of even 0.2% SAP by weight of cement facilitated the successful sealing of 0.2 mm fractures without detriment to the outstanding mechanical capabilities of UHPC. This discovery is noteworthy since UHPC is susceptible to early-age shrinkage cracking, and conventional self-healing methods often compromise its dense structure. The SAPs facilitated internal curative and autogenous healing via regulated water release, assisting in the preservation of internal moisture levels and enhancing further hydration. No strength loss was seen, indicating that SAPs may be compatible with high-performance mixes when properly dosed. The research facilitates the use of SAPs in advanced, robust UHPC structures, such as bridges, precast components, and blast-resistant infrastructure, where durability and strength are paramount. The study emphasizes the feasibility of SAP integration while maintaining performance standards.

Mönnig et al. (2019) investigated the efficacy of super absorbent polymers (SAPs) in shotcrete used for tunnel linings, addressing critical issues of early-age cracking and material rebound. Incorporating 0.3% SAP resulted in a 15% decrease in material rebound and a 20% enhancement in adhesion strength. The enhancements were ascribed to the superior water retention of SAPs, which promoted improved cement hydration and adhesion to the substrate. Moreover, SAP-modified shotcrete demonstrated a 60% self-sealing efficacy for microcracks measuring 0.2 mm, signifying considerable promise for crack mitigation in sprayed concrete applications. The research also observed a decrease in early-age shrinkage fractures, which are vital in tunnel settings where structural integrity and impermeability are paramount. The results highlight the appropriateness of SAPs in sprayed concrete systems, especially for subterranean infrastructure where construction velocity, material efficacy, and longevity are critical. SAPs operate as both crack-healing agents and performance-enhancing additives for shotcrete.

Snoeck and De Belie (2019) devised a dual-action repair method using super absorbent polymers (SAPs) and encapsulated polyurethane (PU) to accommodate a broader spectrum of fracture dimensions in cementitious materials. The PU was engineered to seal bigger fissures (>0.5 mm) by infiltrating the damaged areas upon capsule rupture, whilst SAPs addressed microcracks via moisture absorption and expansion. The combination had an exceptional 85% total fracture sealing efficacy, markedly surpassing SAP-only solutions. The hybrid material demonstrated exceptional efficacy under wet-dry cycling circumstances, with SAPs facilitating moisture retention for ongoing healing and PU providing structural sealing. This method improved durability and long-term resilience, making it appropriate for concrete subjected to variable environmental conditions. The research underscored the synergistic relationship between the two healing processes and stressed the significance of timing and fracture size differential in self-healing design. The study signifies a notable progression in multifunctional, intelligent healing systems for resilient infrastructure.

Park et al. (2019) investigated the synergistic use of super absorbent polymers (SAPs) and polyvinyl alcohol (PVA) fibres in fibre-reinforced concrete to establish a self-healing system. Their research indicated that concrete containing 0.4% superabsorbent polymer and 1% polyvinyl alcohol fibres attained a 50% decrease in crack width and notable enhancements in post-cracking ductility. The PVA fibres facilitated mechanical bridging of macro-cracks, restricting their propagation, whereas SAPs proficiently mitigated microcracks by moisture-induced swelling and sealing. This dual mechanism improved the material's durability and load redistribution capabilities, especially under tensile stress. The integrated solution also reduced early-age cracking and enhanced long-term performance under drying and rewetting circumstances. The researchers highlighted that the collaboration between fibres and SAPs produced a more durable concrete with the ability for self-repair. This work provides robust evidence for the integration of several self-healing techniques to develop advanced concrete composites designed for essential infrastructure subjected to mechanical and environmental stresses.

Yang et al. (2018) examined the influence of super absorbent polymers (SAPs) on the freeze-thaw resilience of concrete, an essential determinant of infrastructure longevity in frigid environments. Their results indicated that the inclusion of 0.5% SAP by weight of cement improved scaling resistance by 40%, mainly due to the creation of micro air gaps that functioned as pressure relief zones during freeze-thaw cycles. These voids mitigated expansion forces from ice formation, hence reducing surface deterioration and fracture propagation. Nevertheless, the research warned that SAP concentration over 0.7% resulted in excessive porosity and subsequent decreases in compressive strength. The authors emphasized the need for adequate SAP dose to reconcile durability improvements with mechanical integrity. This study enhances the comprehension of SAPs as functional additives, not only for self-sealing but also for the reduction of thermal stress. It highlights the potential of SAPs in prolonging the service life of concrete subjected to cyclic freezing and thawing conditions.

Lee et al. (2018) performed a comparative analysis of acrylic acid-based and acrylamide-based superabsorbent polymers, examining their swelling characteristics, healing efficacy, and mechanical impacts on concrete. Acrylic acid superabsorbent polymers shown accelerated swelling kinetics, facilitating rapid fracture closing in humid environments. This fast expansion resulted in a 12% decrease in compressive strength, due to heightened matrix porosity and internal disturbances. Acrylamide SAPs exhibited reduced swelling rates while offering enhanced long-term stability and mechanical retention. After six months, concretes with acrylamide superabsorbent polymers sustained 70% crack healing efficiency, preserving both structural and functional integrity. The research determined that acrylamide-based superabsorbent polymers are better appropriate for long-term infrastructure uses, especially in contexts where healing and durability are critical. These results highlight the significance of chemical composition in SAP selection, necessitating a balance between swelling rate and strength retention, contingent upon environmental exposure and performance criteria of the concrete system.

Hilloulin et al. (2018) used X-ray microtomography to examine the internal impacts of SAPs on the pore structure and healing characteristics of concrete. The imaging demonstrated that SAPs created a network of holes measuring between 20 and 100 µm, which substantially aided autogenous fracture repair by enhancing water retention and distribution. The research demonstrated a clear relationship between pore size distribution and self-healing efficacy, suggesting that a regulated pore architecture improves healing while little affecting strength. An ideal equilibrium was identified whereby SAP-induced holes are sufficiently big to facilitate healing, while remaining tiny and sparse enough to maintain mechanical characteristics. Excessive or irregularly distributed pores resulted in undesired capillary action and a reduction in durability. The study provides a quantitative framework for assessing SAP-modified concrete using microstructural analysis, assisting engineers in optimizing SAP dose and particle size for enhanced performance. These insights facilitate the development of intelligent, self-curing concretes with self-sealing properties.

Jensen et al. (2017) examined the function of superabsorbent polymers (SAPs) in internal curing to mitigate autogenous shrinkage in high-performance concrete. The research determined an ideal SAP dose of 0.2–0.4% relative to cement weight, resulting in a decrease of shrinkage exceeding 80% while maintaining compressive strength. This dose guaranteed enough internal moisture release during initial hydration, averting the onset of capillary strains. SAPs were shown to inhibit plastic shrinkage cracking, particularly in slender concrete parts, where fast moisture loss often occurs. The researchers underscored that accurate SAP sizing and absorption capacity were essential for facilitating prompt water discharge. This study illustrates the significance of SAPs in both mending and alleviating early-age damage processes, hence enhancing the longevity of high-performance structural components. Their results provide a viable framework for using SAPs in structural and architectural applications that need dimensional stability and minimal shrinkage while preserving mechanical integrity.

Snoeck et al. (2017) assessed the impact of supplementary cementitious materials, especially fly ash and slag blends, on late-age fracture healing in blended cements. The research indicated that the use of 0.3% superabsorbent polymer (SAP) with 30% fly ash facilitated 75% fracture closure after 90 days, underscoring the capacity of SAPs to hold and progressively release water for secondary hydration processes. The therapeutic effect was notably pronounced in advanced phases, since pozzolanic reactions in fly ash-based systems rely on continuous internal moisture availability. The collaboration of SAPs and supplemental cementitious materials (SCMs) enhanced microstructural densification and postponed self-healing, essential for enduring performance. Superabsorbent polymers enhanced the sustainability and durability of blended cement systems by optimizing the reactivity of supplementary cementitious materials. The research verifies that SAPs may be strategically used for both early-age curing and prolonging hydration in blended binders, hence facilitating eco-efficient concrete design via material compatibility and delayed healing capabilities.

Wang et al. (2017) initiated the creation of pH-sensitive superabsorbent polymers designed for self-healing concrete applications. In contrast to traditional SAPs, these smart polymers were designed to expand and discharge water only under elevated pH circumstances, which are frequently encountered during crack development. This delayed swelling characteristic inhibited early water release, thereby enhancing healing efficiency by 25% compared to normal SAPs. The pH-responsive method guaranteed that water was supplied exactly when and where required—within fissures during periods of hydration deficiency. The researchers exhibited improved crack closure and sustained hydration, especially in high-performance concrete with low water-to-cement ratios. This work represents a notable progression in SAP technology by including environment-responsive capabilities, hence enabling tailored, condition-specific therapeutic approaches. The study establishes a basis for intelligent material systems that may heal on demand, tackling a primary drawback of conventional SAPs: unregulated swelling and ineffective moisture release in undamaged or non-critical areas.

Mezhov et al. (2016) examined the function of SAPs in alleviating plastic shrinkage cracking in hot climatic settings, mimicking situations with ambient temperatures reaching 40°C. The research indicated that including 0.6% SAP into the mixture decreased plastic shrinkage fractures by 90%, mostly due to internal moisture regulation. The SAPs functioned as tiny water reservoirs, gradually releasing absorbed moisture during initial hydration when evaporation rates were elevated. This moisture preservation mitigated capillary tension formation and surface desiccation, two principal factors contributing to early cracking in hot, arid areas. The research emphasized the potential of SAPs for infrastructure in arid or tropical regions, where fast moisture loss complicates traditional curing techniques. Although increased SAP content may affect workability, the benefits of less cracking and improved early-age performance warranted its use. This study endorses SAP implementation as a viable approach for climate-resilient concrete, particularly in situations where external curing is unfeasible or irregular.

Esteves et al. (2016) examined the impact of superabsorbent polymers (SAPs) on the rheology and workability retention of new concrete, highlighting both obstacles and advantages. The addition of 0.3% SAP elevated the original mix viscosity owing to the water absorption characteristics of the polymer particles. This resulted in improved workability retention, with slump flow sustained for up to 120 minutes, representing a significant improvement compared to SAP-free mixtures. The extended pumpability and placement window renders SAPs appealing for ready-mix and large-scale casting processes. The research highlighted the need of customizing SAP particle dimensions and absorption rates to reconcile flow properties with internal healing efficacy. While elevated viscosities may need modifications to superplasticizers, the advantages in hydration regulation and self-healing capabilities provide an overall enhancement in performance. The study confirms that SAPs perform as multi-functional additives, enhancing both durability and the practical handling and placing of concrete in intricate construction settings.

Kim and Schlangen (2016) investigated a multi-scale self-healing system by integrating super absorbent polymers (SAPs) with superabsorbent fibers in cementitious composites. This hybrid methodology focused on various fracture dimensions: SAPs mitigated microcracks (about 0.1 mm) via moisture release and chemical healing, whilst fibers spanned wider fissures (up to 0.5 mm) to restrict propagation and prevent structural collapse. The fibers ensured mechanical continuity and inhibited fracture propagation, whereas SAPs facilitated CaCO₃ precipitation and sustained hydration, enhancing chemical sealing. The solution shown substantial improvements in fracture closure efficiency and mechanical recovery, making it appropriate for load-bearing and fatigue-sensitive constructions. The study presented an adjunctive healing mechanism that improved durability while maintaining structural integrity. This versatile design is especially advantageous for infrastructure applications subjected to mechanical stresses and environmental stress, such as bridges and industrial floors. The research endorses the use of integrated healing methodologies that include both physical and chemical repair agents to improve resilience.

Snoeck et al. (2015) were pioneers in the experimental validation of the autogenous healing properties of superabsorbent polymers in fractured concrete. Their research shown that the inclusion of 0.3% SAP facilitated fracture closure of up to 0.25 mm, mostly via CaCO₃ precipitation aided by internally released water. Microstructural investigation by SEM demonstrated that the repaired regions recovered 80% of their previous mechanical strength, validating the efficacy of SAPs in reinstating functional performance. The SAPs sustained interior humidity, facilitating ongoing hydration and mineral development even post-crack formation. This study established fundamental evidence for the self-sealing and strength-recovery properties of SAP-modified concrete, presenting a passive but efficient approach to long-term durability. This was a pivotal advancement in the evolution of intelligent, self-repairing materials by establishing a measurable correlation among SAP content, crack healing, and strength restoration. The results endorse SAPs as an effective approach for prolonging the lifespan of concrete structures.

Jensen and Hansen (2015) performed an extensive investigation into the water release kinetics of superabsorbent polymers (SAPs), emphasizing their ability to facilitate internal cure. They found that SAPs may release 60–70% of their absorbed water during the first 7 days, a crucial phase for concrete hydration. This release adequately maintained hydration, minimized autogenous shrinkage, and promoted fracture healing in systems with a low water-to-cement ratio. The research introduced a selection model for SAPs predicated on polymer chemistry, particle size, and compatibility with diverse cement types, recognizing that varying cement formulas influence swelling behavior and release profiles. The study quantified the time and quantity of moisture release, allowing more precise mix formulation for durable, internally cured concrete. Their concept established a solid foundation for selecting SAPs customized to certain structural and environmental criteria. This work continues to be crucial in directing SAP deployment in performance-oriented concrete design.

Pelto et al. (2015) examined the use of superabsorbent polymers in lightweight aggregate concrete, where elevated porosity often undermines strength and durability. By integrating 0.5% SAP, they successfully mitigated the moisture absorption capacity of lightweight aggregates, yielding a 15% increase in compressive strength relative to control mixtures. Furthermore, SAP-modified concrete demonstrated a reduction in shrinkage fractures attributable to enhanced internal curing. The SAPs operated like decentralized water reservoirs, gradually discharging moisture to maintain hydration and alleviate internal tensions. This enhanced microstructural integrity and reduced fracture initiation. The research highlighted the capability of SAPs to improve mechanical performance and dimensional stability in lightweight concrete applications, including precast components and seismic retrofitting materials. It emphasized the need of calibrating SAP dosage in conjunction with aggregate type and cement content to prevent excessive porosity. The research by Pelto et al. advocates for SAP integration in concrete composites that are resource-efficient and structurally resilient, particularly in scenarios where conventional curing methods may be inadequate.

# CONCLUSION

The comprehensive analysis of studies on Super Absorbent Polymers (SAPs) in self-sealing concrete underscores their significant potential to improve infrastructure resilience. Self-healing agents have shown efficacy in autonomously fixing microcracks by moisture-induced swelling and calcium carbonate deposition, attaining up to 90% crack closure in optimised systems. Their capacity to control internal curing markedly reduces shrinkage and alleviates early-age cracking, especially in high-performance and fiber-reinforced concrete. The efficacy of SAPs is contingent upon accurate dose management (often 0.3–0.5% by cement weight), since excessive quantities may elevate porosity and undermine strength. Environmental considerations, like alkaline conditions and salt exposure, affect performance, requiring customised SAP formulations for certain applications. The incorporation of SAPs with other materials such as fly ash or silica fume significantly improves sustainability, making them an effective alternative for resilient and low-maintenance infrastructure.

Recent improvements have broadened SAP uses beyond traditional concrete, including 3D-printed structures, maritime settings, and ultra-high-performance concrete (UHPC). Innovations include pH-responsive superabsorbent polymers, hybrid healing systems (e.g., superabsorbent polymers combined with bacteria or encapsulated polymers), and bio-based alternatives illustrate the material's versatility. These advancements rectify prior deficiencies, including unregulated water discharge and prolonged stability, while enhancing multi-scale fracture remediation. Notwithstanding these achievements, obstacles persist in the standardisation of testing methodologies, the assurance of cost-effectiveness, and the expansion of manufacturing for industrial use. Additional research is required to strengthen SAP compatibility with smart sensors and nanomaterials for real-time monitoring and improved mechanical qualities.

The future of SAP-enhanced self-sealing concrete is rooted on sustainable and intelligent infrastructure solutions. Bio-derived superabsorbent polymers and the incorporation of recycled materials conform to global sustainability objectives, whilst intelligent superabsorbent polymers with stimuli-responsive characteristics facilitate precise healing. Collaboration among academics, engineers, and politicians is crucial for broad acceptance, since it facilitates the establishment of performance criteria and encourages large-scale deployment. By overcoming existing limits and using developing technology, SAP-based concrete may transform building methodologies, providing durable, self-repairing, and climate-resilient infrastructure that satisfies the requirements of contemporary urbanisation and environmental issues.

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