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Self-Healing Recycled Aggregate Concrete: A Comprehensive Review of Materials, Mechanisms, and Emerging Technologies

Prof. Manisha Devidas Bhise

(Assistant professor, Marathwada Mitramandal's Institute of Technology, Lohegaon,
Pune and Research Scholar at Ajeenkya DY Patil University, Pune)

Email id- manisha.bhise@adypu.edu.in

Dr. Arjun.R.Vasatkar

(Associate Professor, School of Engineering Ajeenkya DY Patil University Lohegaon,
Pune and Research Guide at Ajeenkya DY Patil University Pune)

Abstract

The increasing demand for sustainable and durable construction materials has driven the development of innovative solutions such as self-healing recycled aggregate concrete (SH-RAC). This advanced material integrates self-healing mechanisms with recycled aggregate concrete (RAC), addressing both environmental and durability concerns. Conventional concrete structures are prone to cracking, which accelerates deterioration and increases maintenance costs. SH-RAC offers an autonomous crack-repairing capability, significantly enhancing service life. This paper presents a comprehensive review of SH-RAC, focusing on various healing mechanisms including microbial-induced calcium carbonate precipitation (MICP), microcapsule-based systems, and chemical healing approaches. The role of recycled aggregates in improving healing efficiency through internal curing and bacterial immobilization is critically examined. Furthermore, recent advancements such as machine learning-based optimization, surface modification of recycled aggregates, and geopolymer-based SH-RAC are discussed. Key challenges, research gaps, and future directions are also highlighted to support large-scale implementation in sustainable infrastructure.

Keywords: Self-healing concrete, Recycled aggregate concrete, MICP, Microcapsules, Machine learning, Sustainable construction.

I. Introduction

The construction industry confronts a pressing need for sustainable materials and practices to mitigate its substantial environmental footprint. Conventional concrete production significantly depletes natural resources and generates considerable waste, particularly construction and demolition (C&D) debris (Sahu et al., 2022) (Piccinali et al., 2022). Recycling C&D waste into recycled concrete aggregates (RCA) presents a viable pathway to conserve natural resources and reduce landfill volume (Khalid & Abbas, 2023) (Sahu et al., 2022) (Ozbakkaloglu et al., 2018) (Xiao et al., 2019). However, concrete incorporating RCA often exhibits compromised mechanical properties and durability compared to traditional concrete due to the adhered mortar and increased porosity of RCA (Suchithra & Jayashree, 2021) (Ozbakkaloglu et al., 2018) (Kumbhar et al., 2024) (2024). This limitation restricts its broader structural application.

Simultaneously, concrete structures are susceptible to cracking, which compromises their integrity, accelerates deterioration, and necessitates costly maintenance and repair (Durga & Ruben, 2019) (Amran et al., 2022) (Cappellesso et al., 2023). Self-healing concrete, designed to autonomously repair cracks, extends structural service life and reduces maintenance requirements, offering both economic and environmental advantages (Amran et al., 2022) (Liu et al., 2022). The convergence of these two concepts—self-healing mechanisms integrated into recycled aggregate concrete—holds considerable promise for achieving truly sustainable and resilient construction materials. This integrated approach not only addresses the ecological imperative of waste utilization but also enhances the long-term performance of concrete infrastructure. This comprehensive review examines the current state of self-healing recycled aggregate concrete, considering its constituent materials, underlying mechanisms, and advancements in related technologies.

II. Methodology

This review synthesized existing literature on self-healing recycled aggregate concrete. The approach involved systematically identifying and analyzing peer-reviewed articles, conference proceedings, and technical reports focusing on materials, self-healing mechanisms, emerging technologies, and sustainability aspects. The primary objective was to consolidate knowledge regarding the challenges and advancements in this interdisciplinary field. Information was extracted to delineate the properties of RCA, various methods for improving RCA quality, different self-healing techniques applicable to concrete, and the integration of advanced computational tools. The comparative analysis across diverse studies enabled the identification of prevailing trends, performance metrics, and research gaps. Emphasis was placed on evaluating the efficacy of proposed solutions, their environmental implications, and their potential for practical implementation.

III. Literature Review

Materials for Self-Healing in Recycled Aggregate Concrete

Recycled concrete aggregate (RCA), derived from C&D waste, comprises original aggregate and adhered mortar. This adhered mortar often results in higher porosity, increased water absorption, and lower density compared to natural aggregates (NA) (Suchithra & Jayashree, 2021) (Piccinali et al., 2022) (Guo et al., 2018) (Kumbhar et al., 2024) (2024). These characteristics negatively impact the mechanical strength, workability, and durability of recycled aggregate concrete (RAC) (Suchithra & Jayashree, 2021) (Ozbakkaloglu et al., 2018) (Guo et al., 2018). To overcome these limitations, several pretreatment methods have been developed for RCA. Pozzolanic materials, such as fly ash, ground granulated blast furnace slag (GGBS), and microsilica, can coat RCA surfaces, improve their properties and enhance RAC performance (Kumbhar et al., 2024). Studies show that GGBS-coated RCA can lead to significantly higher strength in RAC (Kumbhar et al., 2024). Microbial calcite precipitation also presents a strategy to enhance RCA quality. For instance, biomineralization modified RCA demonstrates reduced water absorption and crushing index, while increasing apparent density (Luo et al., 2024) (Pan et al., 2015) (Feng et al., 2023). This process involves bacteria depositing calcium carbonate in surface pores and microcracks, thereby densifying the aggregate (Luo et al., 2024) (Feng et al., 2023) (Akhtar et al., 2023). Such modified RCA also serve as effective bacterial carriers for self-healing concrete (Luo et al., 2024) (Khushnood et al., 2020).

Self-Healing Mechanisms: Microcapsules, MICP, and Beyond

Self-healing in concrete typically relies on two broad categories: autogenous healing, where intrinsic concrete components react with water to heal cracks, and autonomous healing, involving introduced healing agents . Microbially Induced Calcite Precipitation (MICP) is a prominent autonomous healing mechanism (Raza et al., 2023)(Garg et al., 2022). This process involves specific bacteria, such as Bacillus species, converting organic compounds (e.g., urea) into calcium carbonate ($CaCO_3$) precipitates when activated by water ingress into cracks (Raza et al., 2023)(Garg et al., 2022). These $CaCO_3$ crystals fill and seal the microcracks, restoring structural integrity and reducing permeability (Luo et al., 2024)(Raza et al., 2023)(Akhtar et al., 2023)(Garg et al., 2022). RCA can serve as carriers for these bacteria, enhancing their protection within the concrete matrix and improving healing efficiency (Luo et al., 2024)(Akhtar et al., 2023)(Khushnood et al., 2020). For instance, bacteria immobilized in RCA have effectively sealed cracks up to 1.1 mm wide (Khushnood et al., 2020).

Beyond MICP, other autonomous healing approaches involve the incorporation of microcapsules containing healing agents like polymers or expansive materials (Durga & Ruben, 2019). When a crack propagates and ruptures these capsules, the healing agent is released into the crack plane, polymerizing or expanding to fill the void. Furthermore, crystalline admixtures can stimulate autogenous healing by promoting the formation of calcium silicate hydrate (C-S-H) or $CaCO_3$ within cracks (Durga & Ruben, 2019) (2023). The effectiveness of these mechanisms depends on factors such as crack width, moisture availability, and the longevity of the healing agents.

Emerging Technologies: Machine Learning and Smart Materials

The complexity of designing self-healing recycled aggregate concrete, considering the variability of RCA properties and the intricacies of healing mechanisms, necessitates advanced computational tools. Machine learning (ML) offers a powerful approach for predicting material performance and optimizing mixture designs (Ravikar et al., 2024) (Khan et al., 2024) (Aldawish & Kulasegaram, 2026). ML models can analyze extensive datasets encompassing various concrete mixtures, RCA proportions, and healing agent characteristics to predict mechanical properties, durability, and self-healing rates (Tipu et al., 2024) (Ravikar et al., 2024) (Khan et al., 2024). Studies have demonstrated the efficacy of models like XGBoost, Random Forest, and Gradient Boosting in accurately predicting compressive strength of concrete with RCA (Tipu et al., 2024). Furthermore, ML can optimize mix designs to achieve desired performance while minimizing environmental impact, such as embodied CO_2 emissions (Aldawish & Kulasegaram, 2026).

The application of ML extends to predicting the self-healing performance of RCA concrete. For instance, optimized ML models have shown high accuracy in predicting self-healing rates, with crack width identified as a significant influencing factor. Smart materials, including those with inherent sensing capabilities, could also monitor crack formation and trigger healing processes, though their integration with RCA remains an area for further exploration. The increasing adoption of ML in sustainable construction materials research, particularly for C&D waste, underscores its potential in advancing data-driven solutions for the future of construction (Getachew et al., 2025).

Sustainability and Environmental Impact in Self-Healing Recycled Aggregate Concrete

The integration of self-healing mechanisms with recycled aggregate concrete offers substantial sustainability benefits. Utilizing RCA directly reduces the demand for virgin aggregates, preserving natural resources and diverting C&D waste from landfills (Khalid & Abbas, 2023) (Sahu et al., 2022) (Xiao et al., 2019). By extending the service life of concrete structures and minimizing the need for repairs, self-healing technologies lower maintenance costs, decrease material consumption, and reduce the associated energy and carbon emissions over the structure's lifetime (Liu et al., 2022). Life Cycle Assessment (LCA) studies evaluating self-healing concrete indicate significant environmental advantages, such as prolonged lifespan and reduced carbon emissions. Specific examples include recycled ultra-high-performance concrete (R-UHPC) with self-healing properties, demonstrating environmental benefits and reduced maintenance in aggressive environments (2023).

However, the environmental and economic feasibility of this combined approach must be carefully assessed. While using RCA is generally cost-effective, the incorporation of advanced self-healing agents can increase initial material costs (Liu et al., 2022)For instance, a study on alginate-immobilized microbially induced calcite precipitation (AIMICP) treated RCA found an increase in concrete production cost of 17% to 52% compared to control mixes, though it offered negligible environmental impact increase and improved mechanical properties The use of waste materials, including agro-industrial waste, as supplementary cementitious materials can further reduce costs and enhance sustainability in self-healing concrete (Liu et al., 2022)(Kadamba et al., 2024).

IV. Analysis and Discussion

Performance and Durability Implications

The combination of RCA and self-healing technologies presents a complex interplay of material properties and performance characteristics. Concrete with RCA typically exhibits inferior mechanical properties and durability compared to that made with natural aggregates (Suchithra & Jayashree, 2021) (Guo et al., 2018). Specifically, compressive strength, tensile strength, and elastic modulus often decrease with increasing RCA replacement ratios, particularly above 50% (Khalid & Abbas, 2023) (Ozbakkaloglu et al., 2018) (Nanya et al., 2021) (Mahmood et al., 2021). This reduction is primarily attributed to the high water absorption and porous nature of adhered mortar on RCA, creating weaker interfacial transition zones (Suchithra & Jayashree, 2021).

However, pretreating RCA, for example with biomineralization or pozzolanic coatings, significantly improves its quality, leading to enhanced mechanical properties and durability in RAC (Luo et al., 2024) (Feng et al., 2023) (Dimitriou et al., 2018) (Kumbhar et al., 2024). When self-healing agents are incorporated, particularly bacteria immobilized within RCA, the crack-healing efficiency can be substantial. Studies indicate that bacteria-based recycled concrete can achieve a crack width repair ratio of 94.5% for cracks around 0.4 mm within 56 days, far exceeding that of ordinary RAC (Luo et al., 2024). Such healing not only restores structural integrity but also improves resistance to chloride ion penetration and reduces capillary water absorption, directly addressing key durability concerns of RAC (Luo et al., 2024). The overall performance of self-healing RCA concrete is thus a function of both the quality of the RCA and the effectiveness of the chosen healing mechanism.

Integration Challenges and Practical Considerations

Integrating self-healing technologies into recycled aggregate concrete presents several challenges. The inherent variability in RCA quality, stemming from diverse sources and processing methods, complicates mix design and performance prediction (Piccinali et al., 2022). Ensuring consistent self-healing efficacy across different batches of RAC, especially with varying RCA properties, requires careful control and standardization. The attachment of adhered mortar on RCA affects both mechanical performance and the optimal embedding of healing agents (Kumbhar et al., 2024).

Cost remains a significant practical consideration. While RCA itself can be more economical than natural aggregates, the advanced materials and techniques required for effective self-healing (e.g., specialized bacteria, microcapsules, or crystalline admixtures) can increase initial production costs (Liu et al., 2022). However, these upfront investments are often offset by reduced lifetime maintenance expenses and extended structural durability. Long-term efficacy and robustness of self-healing under realistic environmental conditions (e.g., varying temperatures, humidity, and aggressive chemical exposures) must be rigorously validated before widespread adoption. Furthermore, scaling up laboratory-proven methods to industrial-scale production requires overcoming logistical hurdles related to material handling, mixing, and curing processes.

V. Opportunities and Limitations of Current Approaches

The development of self-healing recycled aggregate concrete offers considerable opportunities for sustainable construction. It provides a dual solution to waste management and infrastructure longevity, aligning with circular economy principles (Sahu et al., 2022) (Makul et al., 2021). Enhanced durability reduces lifecycle environmental impact and costs associated with repairs and early replacement. The ability of RCA to act as a carrier for self-healing agents, such as bacteria, creates a synergistic effect, improving both the aggregate's quality and the concrete's healing capability (Luo et al., 2024) (Akhtar et al., 2023) (Khushnood et al., 2020). Machine learning further accelerates material discovery and optimization, allowing for tailored designs that balance performance, cost, and environmental considerations (Tipu et al., 2024) (Getachew et al., 2025).

Despite these opportunities, limitations persist. Current self-healing mechanisms primarily address microcracks, with their effectiveness diminishing for larger cracks (typically beyond 0.5-1.0 mm) (Luo et al., 2024) (Akhtar et al., 2023) (Khushnood et al., 2020). The long-term viability and survival rates of bacteria in the harsh alkaline environment of concrete remain a subject of ongoing investigation. Furthermore, the lack of standardized testing methods for evaluating self-healing efficiency hinders direct comparison and widespread adoption (Amran et al., 2022). The overall performance of RAC with full replacement levels can still be suboptimal in some cases (Khalid & Abbas, 2023). Continued research is necessary to enhance the robustness of healing agents, expand the crack-healing capacity, and develop comprehensive lifecycle assessment tools for these advanced materials.

VI. Key Findings

Self-Healing Recycled Aggregate Concrete (SH-RAC) combines sustainability with enhanced durability by utilizing recycled aggregates and self-healing mechanisms. It reduces construction waste and conserves natural resources. SH-RAC exhibits effective healing of microcracks through autogenous, bacterial, and encapsulation methods, thereby improving durability and reducing permeability.

However, the use of recycled aggregates can decrease mechanical strength due to higher porosity and water absorption. Optimal performance is achieved with controlled replacement levels and proper mix design. Healing efficiency depends on factors such as crack width, moisture availability, and type of healing agent.

Although initial costs are higher, SH-RAC offers long-term benefits in terms of reduced maintenance and extended service life. Further research is required for standardization, cost reduction, and large-scale implementation.

VII. Conclusion

Self-healing recycled aggregate concrete represents a promising direction for sustainable construction, offering a synergistic approach to address both resource depletion and infrastructure longevity. The utilization of recycled concrete aggregates significantly reduces environmental impact by diverting waste and conserving natural resources. While RCA inherently possesses some drawbacks in terms of mechanical properties and durability, innovative pretreatment methods, including microbial biomineralization and pozzolanic coatings, effectively mitigate these limitations, enhancing RCA quality and subsequently improving the performance of RAC. The integration of self-healing mechanisms, particularly microbially induced calcite precipitation (MICP) where RCA acts as a bacterial carrier, demonstrates substantial crack-healing capabilities, restoring structural integrity and improving durability metrics like water absorption and chloride resistance.

Emerging technologies, notably machine learning, provide powerful tools for predicting the complex interactions within these novel materials, optimizing mix designs, and accelerating the development of high-performance self-healing RCA concrete. Despite the clear benefits, challenges persist, including the variability of RCA properties, the cost associated with advanced healing agents, and the need for robust, long-term validation under diverse environmental conditions. Future research should concentrate on developing more resilient healing agents, expanding the range of healable crack widths, and establishing standardized evaluation protocols. With continued advancements, self-healing recycled aggregate concrete can contribute significantly to a more sustainable, durable, and cost-effective built environment.

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