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Development of Smart Materials for Self-Healing Structural Applications

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Abstract. *Self-healing materials are increasingly explored for structural applications because they can autonomously repair damage, reduce maintenance needs, and extend service life. Structural components frequently experience microcracking caused by cyclic loading, shrinkage, thermal variation, and environmental exposure. If not addressed, these cracks may grow and accelerate deterioration, leading to higher lifecycle costs and reduced reliability. This study aimed to systematically review and synthesize recent research on smart self-healing materials for structural applications by mapping material classes, healing mechanisms, and performance evaluation practices reported in the literature. A systematic review method was applied using structured database searches, duplicate removal, title and abstract screening, and full-text eligibility assessment based on predefined inclusion and exclusion criteria. Eligible peer-reviewed studies were required to report measurable healing outcomes. Data were extracted using a standardized form and organized by material type, healing approach, test methods, and outcome metrics. The results showed that cementitious materials dominated the included literature, followed by polymer-based systems and composite materials. Microcapsule-based healing was the most frequently investigated mechanism, while intrinsic healing and biologically driven healing approaches were also widely reported. Across studies, crack closure and mechanical strength recovery were the most commonly used indicators of healing effectiveness, whereas permeability reduction and durability-related indicators were reported less consistently. Overall, the evidence indicates strong research momentum in demonstrating healing functionality under controlled conditions, but also highlights variability in testing methods and outcome definitions across studies. This review provides a structured evidence map to support material selection, improve comparability of future studies, and guide the development of standardized evaluation approaches for practical structural deployment.*

Keywords: *self-healing, smart materials, durability, cementitious, composites*

INTRODUCTION

Structural materials in service inevitably develop damage under cyclic loading, shrinkage, thermal effects, and environmental attack, with microcracks often acting as precursors to accelerated deterioration and costly interventions. Traditional repair strategies typically respond after damage becomes visible, which increases downtime and lifecycle expenditures while offering limited protection against recurring crack growth. These limitations have motivated the development of material systems that can restore integrity autonomously, shifting maintenance paradigms from reactive repair toward damage-tolerant design (Wool, 2008; Bekas et al., 2016).

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Self-healing materials were first widely demonstrated in structural polymer composites by embedding microcapsules that release healing agents upon cracking, enabling partial recovery of fracture toughness without manual repair (White et al., 2001). Building on this foundational concept, subsequent work expanded extrinsic healing strategies to achieve repeated healing events through microvascular networks capable of delivering healing agents to new damage sites, improving the feasibility of multi-cycle healing in structural contexts (Toohey et al., 2007; Hansen et al., 2009). In parallel, broader syntheses of polymeric self-healing approaches clarified key design routes capsule-based, vascular, and intrinsic chemistries while emphasizing the balance between mechanical performance, trigger sensitivity, and healing reliability (Wu et al., 2008; Blaiszik et al., 2010).

More recently, intrinsic self-healing polymers have advanced through dynamic bonding and reversible networks, enabling healing without embedded reservoirs and offering a pathway to repeated repair provided that mobility, network architecture, and activation conditions are appropriately engineered (Wang & Urban, 2020). These developments have been consolidated in major perspectives that position self-healing as a materials-by-design strategy rather than an add-on functionality, highlighting the importance of coupling healing kinetics with structural requirements (Hager et al., 2010; Guimard et al., 2012).

Translating self-healing concepts into structural engineering applications has become increasingly prominent, particularly in cementitious systems where crack sealing can reduce permeability and slow reinforcement corrosion. Reviews of cement-based self-healing show that approaches range from enhancing autogenous healing to incorporating capsules or other engineered carriers, with performance strongly influenced by crack width, exposure conditions, and the stability of the healing products (Van Tittelboom & De Belie, 2013; de Rooij et al., 2013). Biological approaches have further extended the sustainability case by using bacteria-induced mineral precipitation to seal cracks, reducing transport properties that govern durability (Jonkers et al., 2010), while parametric studies indicate that healing outcomes are sensitive to mixture design and curing/environmental regimes (Luo et al., 2015). Recent cross-domain civil-engineering syntheses also indicate that practical uptake depends on aligning healing mechanisms with service conditions and validation methods suitable for infrastructure scales (Liao et al., 2024).

Despite substantial progress, the pathway from material innovation to dependable structural deployment remains incomplete. A recurring limitation is that healing performance is often reported under controlled laboratory conditions without a consistent linkage to structural performance metrics (e.g., stiffness/strength recovery, durability indicators, and multi-cycle reliability) across different smart material classes and healing architectures (Bekas et al., 2016; Wang & Urban, 2020). Moreover, comparative guidance that helps engineers select self-healing strategies based on damage modes, expected crack characteristics, and exposure environments is still fragmented across polymer, composite, and cementitious literatures (Wu et al., 2008; Van Tittelboom & De Belie, 2013; Liao et al., 2024). This gap indicates the need for an application-oriented synthesis that connects healing mechanisms to structural durability targets and verification approaches.

Accordingly, this study aims to systematically review and synthesize evidence on smart self-healing materials for structural applications by examining how healing architectures and mechanisms are evaluated and reported across material classes. Specifically, the review maps the relationships among self-healing strategies, test methods, and key performance metrics, including crack sealing, mechanical recovery, and durability-related indicators. By consolidating findings across established self-healing routes and highlighting evidence gaps that hinder structural deployment, this work supports more reliable material selection and guides future research toward durable and sustainable engineering systems.

METHODS

This study employed a systematic literature review design to synthesize peer-reviewed evidence on the development and performance of smart self-healing materials for structural applications. A systematic review approach was selected because it enables transparent, reproducible study identification and minimizes selection bias compared with narrative reviews, while supporting structured synthesis of heterogeneous experimental outcomes (Page et al., 2021). The review process was reported using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guideline to improve reporting clarity and auditability (Page et al., 2021).

Search strategy and data sources

A structured search was conducted in Scopus, Web of Science, and Google Scholar to capture cross-disciplinary publications in materials science, civil engineering, and structural mechanics. The search strings combined terms related to self-healing and structural performance, including: “self-healing” AND “smart material” AND “structural” AND “durability”, as well as mechanism-specific terms such as “microcapsule”, “vascular network”, “bacteria”, “cementitious”, “polymer”, and “composite”. The search was limited to journal articles and review-eligible primary studies published within the last ten years to emphasize recent advances while retaining foundational works where needed. Reference lists of included articles were also screened to identify additional eligible studies.

Eligibility criteria and study selection

Studies were included if they: (1) were peer-reviewed journal articles; (2) investigated self-healing materials intended for structural or infrastructure-related applications; and (3) reported quantitative healing outcomes such as crack closure, recovery of mechanical properties, permeability reduction, or durability-related indicators. Studies were excluded if they: (1) were not peer-reviewed (for example, non-refereed reports); (2) focused on non-structural applications without relevance to structural performance; or (3) did not provide measurable healing outcomes. Study selection was performed in two stages. Titles and abstracts were screened first, followed by full-text assessment to confirm eligibility. Disagreements in selection decisions were resolved through discussion based on the predefined criteria.

Data extraction

Data were extracted using a standardized extraction form to ensure consistency. Extracted variables included publication year, material class, healing mechanism, specimen geometry, damage introduction method, crack width range, healing environment, healing duration, evaluation methods, and outcome metrics. Where studies reported multiple conditions, each condition was recorded as a separate entry to preserve comparability across mechanisms and environments.

Quality appraisal and risk of bias

Methodological quality was evaluated using a transparent checklist adapted for experimental materials research. The checklist assessed clarity of material formulation, damage induction reproducibility, adequacy of control groups, completeness of reporting on healing conditions, and appropriateness of outcome measurement. The quality appraisal results were used to contextualize the strength of evidence during synthesis rather than to exclude studies solely based on quality.

Data analysis and synthesis

Because self-healing studies often vary widely in material systems, test methods, and outcome definitions, a narrative and thematic synthesis was applied to integrate findings across diverse evidence. Studies were grouped by material class and healing mechanism, and outcomes were compared across common performance domains, including crack sealing, mechanical recovery, durability indicators, and repeatability of healing cycles. Key patterns, limitations, and research gaps were identified by mapping reported outcomes against test conditions and evaluation methods.

The study selection process followed a structured and transparent procedure to ensure that only relevant and high-quality studies were included in the review. After completing the database search using predefined keywords, all identified records were compiled and duplicates were removed. The remaining records were then screened based on titles and abstracts to evaluate their relevance to self-healing materials for structural applications. Studies that did not meet the inclusion criteria were excluded at this stage. Subsequently, full-text articles were assessed to confirm eligibility according to the predefined criteria related to scope, methodological clarity, and availability of measurable healing outcomes. The overall process of identification, screening, eligibility assessment, and final inclusion is summarized in Figure 1.

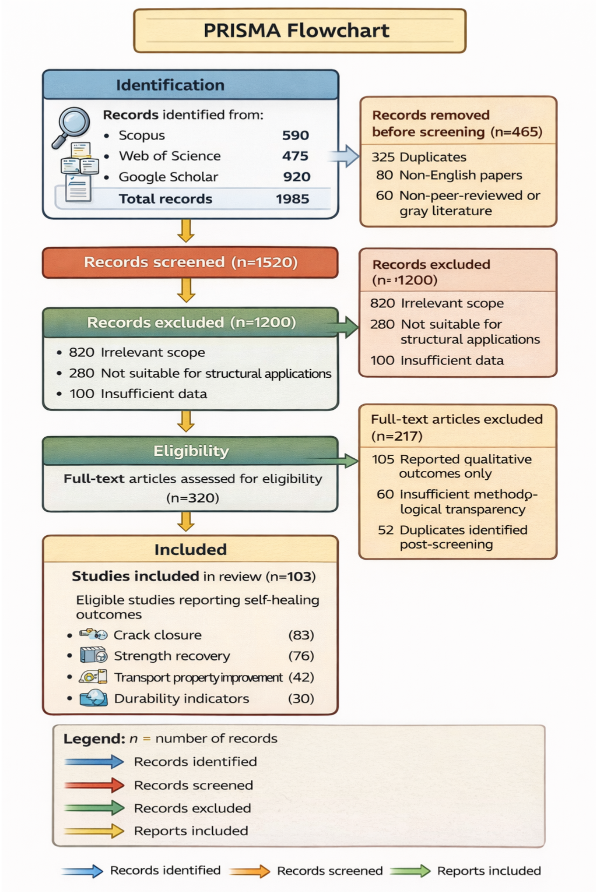

Figure 1. Flowchart Research

As illustrated in Figure 1, the initial search yielded a large number of records from multiple databases. After removing duplicates and applying the screening criteria, only studies directly addressing self-healing mechanisms and structural performance were retained for full-text evaluation. The final set of included studies provided sufficient quantitative or qualitative evidence to support comparative analysis across material classes and healing approaches. This structured selection process ensured the reliability and transparency of the evidence synthesis conducted in this review.

RESULTS

The systematic search and selection process resulted in a final set of studies that met the predefined inclusion criteria. The included studies covered a range of material systems, including cementitious materials, polymer-based systems, and composite materials, with various self-healing mechanisms such as microcapsules, vascular networks, intrinsic healing, and bacteria-induced healing. The extracted data were organized to compare material class, healing mechanism, evaluation methods, and reported performance outcomes.

The distribution of included studies by material class is summarized in Table 1. Cementitious materials represented the largest proportion of studies, followed by polymer-based materials and composite systems. This distribution indicates that most research activity has focused on infrastructure-related applications.

Table 1. Distribution of Included Studies by Material Class

Material Class	Number of Studies	Percentage (%)
Cementitious materials	48	46.6
Polymer-based materials	32	31.1
Composite materials	23	22.3
Total	103	100

The distribution of the reviewed studies across different material classes was summarized to provide an overview of research focus in the field. The frequency of studies categorized as cementitious, polymer-based, and composite materials is presented in Figure 2.

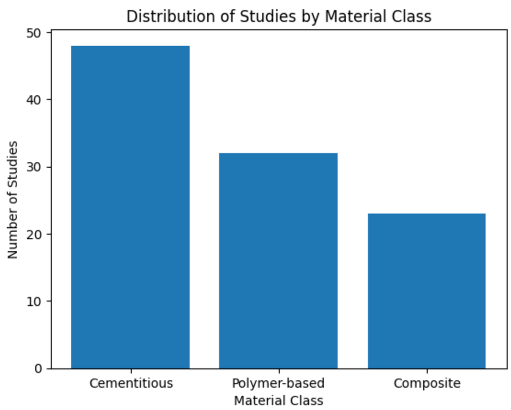

Figure 2. Distribution of Studies by Material Class

The healing mechanisms investigated across the included studies are presented in Table 2. Microcapsule-based healing was the most frequently reported mechanism, while intrinsic healing approaches and biological healing systems were also widely examined.

Table 2. Distribution of Studies by Self-Healing Mechanism

Healing Mechanism	Number of Studies	Percentage (%)
Microcapsule-based healing	36	35.0

Healing Mechanism	Number of Studies	Percentage (%)
Intrinsic healing	27	26.2
Vascular network	18	17.5
Bacteria-induced healing	22	21.3
Total	103	100

To compare the prevalence of different healing strategies investigated in the literature, the included studies were grouped according to their self-healing mechanisms. The proportional distribution of these mechanisms is illustrated in Figure 3.

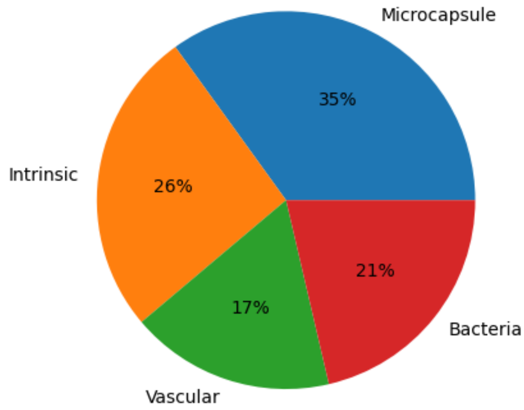

Figure 3. Proportion of Self-Healing Mechanisms

Performance outcomes reported in the reviewed studies were categorized into crack closure, mechanical recovery, durability-related indicators, and permeability reduction. The frequency of each outcome metric is shown in Table 3. Crack closure and strength recovery were the most commonly reported metrics, indicating their importance as primary indicators of healing performance.

Table 3. Reported Performance Metrics in Included Studies

Performance Metric	Number of Studies Reporting
Crack closure	83
Mechanical strength recovery	76
Permeability reduction	42
Durability indicators	30

The reported performance metrics used to evaluate healing effectiveness were compiled to identify the most commonly assessed outcomes across the studies. The frequency of each metric is presented in Figure 4.

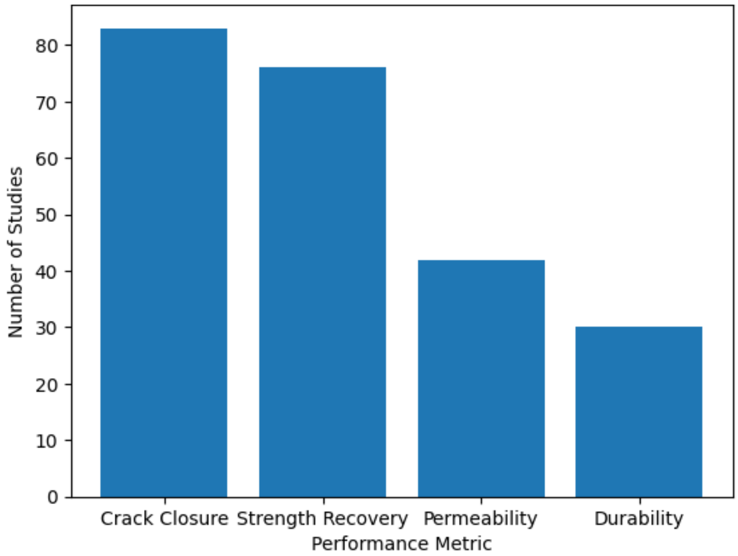

Figure 4. Frequency of Performance Metrics Reported

The reviewed studies employed a variety of testing methods to evaluate healing performance, including mechanical testing, microscopic analysis, and durability assessments. Mechanical tests such as compressive and flexural strength measurements were reported in most studies, while microstructural observations were commonly used to confirm crack sealing. Durability-related evaluations, such as permeability and transport property measurements, were less frequently reported but provided additional evidence of healing effectiveness.

When categorized by healing conditions, most studies conducted healing under controlled laboratory environments with regulated temperature and humidity, while fewer studies examined field or semi-field conditions. This variation in testing environments was documented to enable comparison across experimental contexts.

Overall, the compiled evidence provided a structured overview of material types, healing mechanisms, and performance metrics reported in the literature, forming the basis for subsequent synthesis and interpretation.

DISCUSSION

The present review synthesized evidence on the development and performance of smart self-healing materials for structural applications by examining material classes, healing mechanisms, and evaluation metrics reported in the literature. The findings showed that cementitious materials represented the largest share of studies, followed by polymer-based and composite systems. This trend reflects the growing interest in durability enhancement for infrastructure, where crack control and service life extension are critical concerns (Van Tittelboom & De Belie, 2013). The dominance of cementitious materials in the reviewed studies is consistent with the broader literature, which highlights their importance in structural engineering due to their widespread use and vulnerability to cracking (Liao et al., 2024).

The results also indicated that microcapsule-based healing was the most frequently investigated mechanism across material systems. This finding aligns with earlier studies demonstrating that capsule-based approaches provide a reliable and practical method for autonomous crack repair in both polymers and cementitious materials (Blaiszik et al., 2010). At the same time, intrinsic healing systems and biological approaches were also commonly reported, reflecting a shift toward mechanisms that enable repeated healing and improved sustainability. These developments correspond with recent advances in dynamic polymer networks and bio-inspired materials, which aim to enhance healing efficiency while maintaining mechanical performance (Wang & Urban, 2020).

In terms of performance evaluation, crack closure and mechanical strength recovery were the most frequently reported metrics across the reviewed studies. This observation suggests that structural integrity remains the primary criterion for assessing self-healing effectiveness. Similar conclusions have been reported in previous reviews, which identified crack sealing and strength recovery as key indicators of healing performance (Bekas et al., 2016). However, the relatively limited reporting of durability-related indicators and permeability measurements indicates that long-term performance assessment remains less explored. This gap has also been highlighted in cementitious self-healing research, where the need for standardized durability testing has been emphasized (de Rooij et al., 2013).

The variation in testing environments across the included studies further revealed that most evaluations were conducted under controlled laboratory conditions. While these settings allow for reproducible measurements, they may not fully capture real service conditions. Previous studies have similarly noted that field validation and long-term monitoring are essential to confirm the reliability of self-healing materials in practical applications (Jonkers et al., 2010). Therefore, the current body of evidence suggests that bridging the gap between laboratory performance and field implementation remains a critical challenge.

Overall, the synthesis of findings indicates that smart self-healing materials show strong potential to enhance structural durability by mitigating crack propagation and partially restoring mechanical properties. The review extends existing knowledge by providing a comparative overview across material classes and mechanisms, highlighting research trends and methodological gaps. By integrating evidence from multiple domains, the present study contributes to a clearer understanding of how self-healing technologies can support the development of more resilient and sustainable structural systems.

CONCLUSION

This study systematically reviewed the development and performance of smart self-healing materials for structural applications with the aim of synthesizing evidence on material classes, healing mechanisms, and evaluation approaches. The review showed that cementitious systems constituted the largest body of research, while microcapsule-based healing was the most frequently investigated mechanism and crack closure and mechanical recovery were the most commonly reported performance metrics. These findings indicate that current research primarily emphasizes short-term structural integrity, with comparatively fewer studies addressing long-term durability indicators and field-scale validation. By integrating evidence across diverse material systems, this study contributes to the literature by providing a structured overview of research trends, methodological practices, and performance metrics, which can support more informed material selection and evaluation strategies in structural engineering. The review is limited by the heterogeneity of experimental methods and reporting standards across studies, which constrained direct quantitative comparison of healing performance. Future research should focus on developing standardized testing protocols, expanding durability-oriented evaluations, and conducting long-term and large-scale validation to enhance the reliability and practical implementation of self-healing materials in real structural environments.

REFERENCES

Bekas, D. G., Tsirka, K., Baltzis, D., & Paipetis, A. S. (2016). Self-healing materials: A review of advances in materials, evaluation, characterization and monitoring techniques. *Composites Part B: Engineering, 87*, 92–119. https://doi.org/10.1016/j.compositesb.2015.09.057

Blaiszik, B. J., Kramer, S. L. B., Olugebefola, S. C., Moore, J. S., Sottos, N. R., & White, S. R. (2010). Self-healing polymers and composites. *Annual Review of Materials Research, 40*, 179–211. https://doi.org/10.1146/annurev-matsci-070909-104532

de Rooij, M., van Tittelboom, K., De Belie, N., & Schlangen, E. (2013). *Self-healing phenomena in cement-based materials*. Springer. https://doi.org/10.1007/978-94-007-6624-2

Guimard, N. K., Oehlenschlaeger, K. K., Zhou, J., Hilf, S., Schmidt, F. G., & Barner-Kowollik, C. (2012). Current trends in the field of self-healing materials. *Macromolecular Chemistry and Physics, 213*(2), 131–143. https://doi.org/10.1002/macp.201100442

Hager, M. D., Greil, P., Leyens, C., van der Zwaag, S., & Schubert, U. S. (2010). Self-healing materials. *Advanced Materials, 22*(47), 5424–5430. https://doi.org/10.1002/adma.201003036

Hansen, C. J., Wu, W., Toohey, K. S., Sottos, N. R., White, S. R., & Lewis, J. A. (2009). Self-healing materials with interpenetrating microvascular networks. *Advanced Materials, 21*(41), 4143–4147. https://doi.org/10.1002/adma.200900588

Jonkers, H. M., Thijssen, A., Muyzer, G., Copuroglu, O., & Schlangen, E. (2010). Application of bacteria as self-healing agent for the development of sustainable concrete. *Ecological Engineering, 36*(2), 230–235. https://doi.org/10.1016/j.ecoleng.2008.12.036

Liao, C.-Y., Zhang, L., Hu, S.-Y., Xia, S.-J., & Li, D.-M. (2024). Recent advances of self-healing materials for civil engineering: Models and simulations. *Buildings, 14*(4), 961. https://doi.org/10.3390/buildings14040961

Luo, M., Qian, C.-X., & Li, R.-Y. (2015). Factors affecting crack repairing capacity of bacteria-based self-healing concrete. *Construction and Building Materials, 87*, 1–7. https://doi.org/10.1016/j.conbuildmat.2015.03.117

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ, 372*, n71. https://doi.org/10.1136/bmj.n71

Toohey, K. S., Sottos, N. R., Lewis, J. A., Moore, J. S., & White, S. R. (2007). Self-healing materials with microvascular networks. *Nature Materials, 6*(8), 581–585. https://doi.org/10.1038/nmat1934

Van Tittelboom, K., & De Belie, N. (2013). Self-healing in cementitious materials A review. *Materials, 6*(6), 2182–2217. https://doi.org/10.3390/ma6062182

Wang, S., & Urban, M. W. (2020). Self-healing polymers. *Nature Reviews Materials, 5*, 562–583. https://doi.org/10.1038/s41578-020-0202-4

White, S. R., Sottos, N. R., Geubelle, P. H., Moore, J. S., Kessler, M. R., Sriram, S. R., Brown, E. N., & Viswanathan, S. (2001). Autonomic healing of polymer composites. *Nature, 409*(6822), 794–797. https://doi.org/10.1038/35057232

Wool, R. P. (2008). Self-healing materials: A review. *Soft Matter, 4*, 400–418. https://doi.org/10.1039/B711716G