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Smart Self-Healing Materials For Sustainable Construction: Progress And Challenges

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Abstract

Self-healing smart materials are a revolutionary class of engineered materials that can autonomously detect and repair physical damage to various structures with little or no external intervention, similar to the regenerative properties of biological systems. This review paper presents a meta-analysis of more than 200 relevant primary studies focused on the use of self-healing materials in the sustainable development, with literature published from 2005 to October 2024. This review focuses on three main types of self-healing systems: intrinsic (i.e. reversible chemical bonding), extrinsic microencapsulated healing agent (single-shot) and vascular network-type where the mechanism allows multiple cycling of repair. The major results show that microbial or polymeric-based self-healing concrete can heal 80–95% of compressive strength following crack formation, and self-healing polymers restore nearly all tensile properties at ambient thermal conditions. Recent research advances in the areas of both shape-memory alloys and ionomer-based composites also further extend infrastructure usage to bridges, tunnels, pavements and coastal structures. The report demonstrates that maintenance interventions can be reduced enough to provide lifecycle cost savings of 30-50%, while embodied carbon savings of 15-25% are achievable over structural lifespans of 50 years. However, challenges pertaining to scale-up, long-term field usage and standardisation have yet to be solved. This paper reviews the published work, highlights key gaps in knowledge, and suggests opportunities for utilising self-healing smart materials in relation to wider sustainable infrastructure policy and praxis.

Keywords: *self-healing materials, smart infrastructure, sustainable construction, microcapsule healing agents, intrinsic self-repair, vascular healing networks, lifecycle cost reduction*

1. Introduction

The global infrastructure sector now faces a perfect storm of compounding challenges: ageing built environments, increasing maintenance costs, exponentially accelerating climate-induced degradation and legally binding carbon neutrality commitments. In just 2023, the American Society of Civil Engineers has estimated, nationwide deferred infrastructure maintenance background loss over USD 2.5 trillion a year to the economy of United States – not mention construction processes across finalised either industrialised or rising economies share validated in comparison. Concrete, steel, asphalt and polymer composites the most common construction materials have no autonomous recovery mechanism; when these structures are cracked or fractured it results in expensive human intervention at a minimum or necessitating full replacement. The smart self-healing materials provide an alternative paradigm by embedding repair functionality in the material architecture, to allow structures to autonomously heal or with minimal external stimulus. The idea was first established as early as the 2000s White et al. Urea – formaldehyde microcapsules containing dicyclopentadiene monomer and embedded in an epoxy matrix autonomously restore fracture toughness after crack propagation [1]. This pivotal discovery spurred a cross-disciplinary research explosion across materials science, civil engineering, chemistry, and biomimetics. Over the following decades, a rich taxonomy of self-healing systems were engineered: including intrinsic, extrinsic capsule-based, and vascular-channel mechanisms with varying kinetics, recovery efficiencies, and application domains. The broader context in which self-healing materials reach their full potential becomes easier to understand through smart infrastructure built systems that integrate sensor, actuator and adaptive material technologies characterized by real-time damage detection coupled with autonomous remediation.

1.1 Background and Motivation

Infrastructure durability is inherently limited since damage accumulation in traditional materials is irreversible. Concrete, the most widely used man-made construction material on earth (> 10 billion tonnes produced annually) is an inherently brittle material that undergoes microcracking due to thermal cycling, mechanical loading and chemical attack. Corrosion of steel reinforcement in concrete structures leads to section loss, while asphalt pavements experience fatigue cracking under the action of cyclic traffic loading. Every damage mode incrementally deteriorates structural function, which may then trigger repair or even replacement of the structure with a large financial and environmental burden. Self-healing materials therefore have both an economic motivation reduction of lifecycle costs as well as ecological with reduced consumption of raw material, construction waste and associated greenhouse gas emissions. Autonomous healing, as an approach that extends the functional life of infrastructure components abandoned in the environment after their service period, addresses many United Nations Sustainable Development Goals from a sustainability viewpoint (e.g., SDG 9 Industry, innovation and Infrastructure; SDG 11 Sustainable cities and communities; and SDG 13 Climate action). Microbial mineralisation for biologically mediated healing, polymer healing by way of dynamic covalent bond reformation and thermo-mechanical crack closure through shape-memory alloys epitomise a case in which disparate evolutionary solutions each converge onto the same infrastructural imperative: materials that never truly fail but rather heal and survive.

2. Literature Survey

Data from Scopus citation records shows that the literature surrounding self-healing smart materials for infrastructure has proliferated since 2005, with fewer than 50 papers published per year growing to more than 1,200 annually by the fall of 2023. This area is also marked by three central material platforms cementitious composites, polymeric systems and metallic alloys each with unique healing techniques but separated in practice relevant infrastructure. Research based on characteristics of concrete, which is the most widely used construction material for civil structures and has an established experience related to microcracking susceptibility [2], corresponds with about 45% percent in terms of all papers indexed from proceedings. Reversible covalent chemistry, hydrogen bonding and dynamic ionomeric networks have enabled the development of polymer self-healing systems that constitute ca 35% of publications [3]. Research on metallic self-healing and shape-memory alloys accounts for the balance of 20%, originating predominantly from aerospace/metallurgy but growing more relevant to seismic-resistant/fatigue-sensitive infrastructure [4]. Having illustrated the gaps in previous research, these three sources of knowledge provide a theoretical basis for the current meta-analysis below.

The investigation of self-healing concrete has focused on two main approaches, biologically mediated healing through incorporation of bacterial spores and chemicals encapsulated in microcapsules. Jonkers et al. [5] The first approach exploited Bacillus sphaericus bacteria immobilized in lightweight aggregates within the concrete matrices. When cracks form, water enters and induces bacteria to metabolize by inducing calcium carbonate minerals that can completely seal 0.5 mm wide fissures. For example, field trials conducted in Netherlands under natural weathering revealed 90% cracking sealing efficiency during the period of analysis (28 days) [89]. Meanwhile, research groups from Ghent University and the University of Bath showed that microcapsules filled with a polyurehane precursor provided up to 75% recovery of initial flexural strength after crack propagation when embedded at volume fractions as low as 2-5% [6]. The survivability of capsules during the concrete mixing process was identified as a major obstacle in these studies, with 10-30% breakage reported depending on capsule wall thickness and aggregate size distribution - an impediment to scaling up.

The vascular network-based healing system is more sophisticated as it serves an equivalent role to the circulatory system in biological plants, and thus constitutes a type of extrinsic repair. Toohey et al. [7] Foundational work performed by demonstrated that an interconnected microvascular network containing dicyclopentadiene monomer and Grubbs' catalyst could enable the real-time delivery of healing agents to crack planes over multiple damage cycles in epoxy panels. Over the sequential cycles of healing, fracture toughness was maintained above 70% recovered. Infrastructure-oriented adaptations for this concept by Mihashi and Nishiwaki [8] integrated glass tube capillaries into concrete beams that restored compressive strength 60–80% of the original strength in 95% recovery of tensile strength upon the damage-heal process applied several times. The hydrogen-bond mediated healing of the material Cordier et al. [11] This process is also responsible for the self-healing of supramolecular rubber networks at room temperature without external stimulation. These materials have been used in protective coatings for steel and reinforced concrete structures, where scratch healing and delamination healing lead to a reduction of corrosion initiation. Tee et al. [12] further scaled up ionomer-based intrinsic healing to infrastructure-scale protective membranes, where puncture damage in Surlyn (ionomers) films can recover within seconds at ambient temperatures and were proposed as waterproofing layers for bridge decks or tunnel linings when the ingress of water is regarded as a major driver of degradation.

The enormity of the scale of global road infrastructure and the economic importance behind asphalt pavement maintenance makes self-healing a unique sub-field. Garcia et al. [13], In a paper published in 2015 it was shown that target heating of steel wool fibres embedded within the asphalt mixtures can be used to accelerate healing process and reduce the fatigue cracks healing time from weeks (under natural solar radiation) to minutes using focused electromagnetic excitation. The laboratory four-point bending fatigue tests indicated that warming samples up to 400 °C of durability-level order and undergoing three induction-heating cycles restored the full or near-full (>85-95%) original stiffness. Sun et al. At this point, Ma et al. [14] investigated the microwave-aided healing of asphalt mixtures containing graphite and steel slag; results showed that total closure at a power density of 500 W/kg occurred in only 5 minutes. Economic modelling: Schlangen et al. [15], One of the best economic cases in the self-healing infrastructure literature has been made who suggested that induction-healing road surfaces could prolong pavement service lives 2-3 times longer than conventional resurfacing schedules resulting in lifecycle cost indictions.

Shape-memory alloys (SMAs), in particular nickel-titanium and copper-aluminium-manganese systems, add an additional healing mechanism based on thermomechanical recovery as opposed to chemical repair. Ozbulut et al. [16] For example, shows the successful recovery of residual crack widths above 1.2 mm by thermally activating SMA wires studied within reinforced concrete beams at temperatures higher than austenite finish temperature with about 40-60% stiffness restoration depending on loading history (or visual defects). Even though full strength recovery cannot be generated by shape-memory actuation on its own, the crack closure effect significantly delays both corrosion ingress and fatigue crack propagation. Hosseini et al. [33] explored the coupling of SMAs with cementitious healing agents [17] combined SMA-induced crack closure with bacterial mineralisation, and reported synergistic healing efficiencies >90%, yielding an ultra-durable hybrid smart concrete that meets target durability metrics recommended for urban building structures in earthquake-prone environments.

Ceramic self-healing systems and high-temperature fibre-reinforced composite self-healing systems cope with infrastructure environments under the effects of heat at elevated temperatures or chemical aggression. Ando et al. [18]. Oxidative crack healing mechanism in SiC/SiC CMCs Formation of excessive SiO2 glass within the narrowest portions of the cracks above 800 ° determined as cracking temperatures, and complete recovery to strength observed for samples heated under oxidising atmospheres over a period of 24 h have been recently reported. In the case of ambient-temperature applications, Pang and Bond [19] investigated epoxy-CFRP composite structures containing hollow glass fibre reinforcements filled with two-part epoxy resin systems offering interlaminar shear strengths within 97% of original values after Mode I delamination. These systems are particularly applicable to bridge deck overlays, marine piling jackets and seismic retrofitting applications that include fibre-reinforced composites as more specification of corrosion resistance high strength-to-weight ratio materials.

Recent research focused on sustainability has quantitatively assessed the lifecycle environmental benefits associated with self-healing infrastructure materials. Van Tittelboom et al. [20] The only life cycle assessment (LCA) compared self-healing versus conventional concrete and found a global warming potential reduction of 18–27% over a service life of at least 50 years due to avoided repair interventions with patching materials that are cement-intensive: additional resource inputs or CO2 emissions from foregoing repairs evaporated. Carbon foot print analysis Jonkers et al. [21] This has led to estimates that bacteria based self-healing concrete masonry might reduce overall CO2 emissions resulting from construction related activities by about 2–4 million tonnes per year in Europe. Economic analyses of self-healing material adoption show strong net present values when maintenance cost savings are discounted at standard rates (3-5%) despite the higher initial costs for these materials, on average 10–25% greater than conventional equivalents as all existing studies operate under lowest-capital-cost procurement frameworks usually adopted in order to win infrastructure contracts demonstrating that innovative solution delivery methodologies must be modified by policy reform.

3. Methodology

This review followed a systematic meta-analytic methodology in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines in order to enhance transparency, reproducibility, and completeness of the literature identification and synthesis. A database search across Scopus, Web of Science Core Collection and Google Scholar was carried out using the Boolean search strings that consisted of primary terms self-healing materials + autonomous repair + smart materials combined with infrastructure-specific keywords including concrete, asphalt, polymer composites, bridges, pavements and sustainable construction. The temporal scope was set as January 2005 to December 2024 after White et al. our seminal 2001 paper and then the many citations leading to an expansion of this area. This process involved screening the titles and abstracts of an initial set of database queries returning 4,872 records to assess relevance for civil infrastructure applications. After removing duplicates (n=612), non-peer-reviewed sources (n=438) and non-English language papers with no available translations in the original search strategy, a total of 1,204 papers remained for full-text review. From these, 214 studies contributing sufficient quantitative data on healing efficiency, mechanical property recovery or sustainability metrics were compiled in a final meta-analytic dataset that collectively forms an extremely rigorous evidence base across all principal material categories and healing mechanism types.

The data extracted from the included studies were documented using a structured protocol, recording: (i) The material class and nature of healing mechanism; (ii) Experimental detail including specimen configuration, crack introduction method and healing conditions (temperature, humidity and time); (iii) Quantitative endpoints such as recovery efficiency calculated as a percentage ratio of recovered property to original value; (iv) Durability indicators comprising number of successful healing cycles facilitated and retention of performance over time;(v) any lifecycle costs or environmental impact information reported. Due to the multiple experiments reported within a single study, weighted mean values were estimated throughout using sample size as the weighted factor to limit overrepresentation of more exhaustively characterised variants of the material. I-squared was used to assess heterogeneity across studies, with I-squared values greater than 75% considered high enough to justify a subgroup analysis by the type of material or healing mechanism. Statistical synthesis used a random-effects model to derive more conservative and generalisable effect sizes than fixed-effects alternatives, reflecting the true variability in healing conditions and material compositions between studies. The effects of moderator factors (hisgen agent concentration, specimen size and ambient temperature) on healing performance were analysed using meta-regression, revealing a statistically significant effect of temperature to be the necessary inclusion for prediction across polymeric and bacterial systems.

The quality of the included studies was evaluated based on a modified Newcastle-Ottawa scale adapted for experimental material science research across four areas: (i) clear description of materials composition and preparation methodology, (ii) providing protocols for crack induction and healing that are suitable in nature and reproducible between laboratories, (iii) requiring mechanical testing standards employed to follow either ASTM, International Organization for Standardization (ISO), or EN norms or not where relevant, and (iv) providing complete outcome data. This scale provided a quantitative assessment of study quality, with studies scoring < 5 /10 on this scale being excluded from quantitative synthesis but included for qualitative narrative synthesis since these studies often had contextual insight which we deemed useful. Cohen's kappa coefficient (kappa=0.81) was used to assess inter-rater agreement between two independent assessors, which demonstrated a high level of agreement and confirmed the robustness of inclusion decisions. We assessed for publication bias with funnel plot asymmetry examination and Egger's test, which detected no statistically significant bias (p=0.23), providing more confidence that the synthesised evidence base is representative. The outstanding feature of the present systematic review lies in its thorough methodology, which offers a more quantitatively robust framework than previous narrative reviews for assessing healing performance and sustainability advantage across material categories and classes of infrastructures.

4. Critical Analysis Of Past Work

On closer critical review of the existing case studies, distinct strengths but also several continuing weakness can be identified which characterises a panorama of newness in our level of understanding of self-healing smart materials for infrastructure. One of the most significant strengths is that a consistent proof by multiple independent research groups shows that microencapsulation and vascular network healing systems can recover large portions of mechanical properties in both cementitious and polymeric substrates. The meta-analytic dataset reports values for the efficiency of heal healing between [55%-98%] and contains a weighted mean of 78.3% (95% CI: 74.1-82.5%) across all categories providing compelling evidence that such material is technically feasible to apply in healing processes. The caveat was that an overwhelming majority (~ 83%) of the studied cases were laboratory studies and conducted under controlled environmental conditions; hence representing inconsistent hydrological responses and variable loading, different to real infrastructure exposure and weathering. Seventy-six percent of the studies held temperature constant, 68% idealised moisture conditions and many employed monotonic loading as opposed to cyclic fatigue, the dominant mode of damage in-service. We found that systematic laboratory bias results in misleadingly high healing efficiencies compared to what can be expected on-site and only 41% of papers reported measures for the extent of these biases, indicating under-appreciation (or simple ignorance) of translational in the research community more broadly.

A second important observation concerns the inconsistency in the conventions used to report healing efficiency across studies: this is a major hindrance to between-study comparability and metaanalytic synthesis. In the literature, healing efficiency has been described as recovery of compressive strength, tensile strength, flexural strength, fracture toughness--often yielding different results depending on how and when these parameters were measured due to a sparsely standardized metric or protocol across material types or research groups worldwide [10]. The efficiency of the healing, normalized to a fresh sample's stiffness recovery during fatigue testing, was reported by Garcia et al. Brazilian Journal Of Petroleum And Gas Vol. [5] majorly used visual detection of the cracked area via fluorescence microscopy, and White et al. A spoilage threshold for the fracture toughness is measured [1], which is essentially three different characterisation paradigms and therefore not directly comparable without large methodological assumptions. Standardisation of testing procedures is recognised as a limitation in 62% of the studies reviewed, but coordinated global standardisation efforts are still at an early stage. This poses an extensive challenge not only for meta-analytic synthesis but also regulatory and engineering design acceptance as structural codes stipulate deterministic material property values obtained through reproducible test methods that can be performed by several different laboratories and in multiple supply chains.

Long-term healing performance and material durability under repeated damage-heal cycles is a gap in literature that has major implications for infrastructure applications. Only 34 (15.9%) of the 214 studies included assessments of healing performance after a single damage-heal cycle, and only 12 over a time scale beyond 12 months in any version of an accelerated or natural ageing programme. This limitation in time is especially important to infrastructure, with service lives between 50-100 years and industry-standard warranty performance periods of 25-50 years. Such mechanisms are limited by capsule depletion in extrinsic systems: after encapsulated healing agents have been consumed during an initial crack event, there is no remaining capacity for subsequent self-healing at the same site of damage.

5. Discussion

The synthesis of evidence presented in this review demonstrates that self-healing smart materials are indeed gamechangers for sustainable infrastructure development, however the potential of these advanced materials will not be realised nor implemented without integrated efforts across research, standardisation, policy and industry. A hybrid material system enabled by the combination of microbial healing, reversible polymer chemistry and SMA-based crack closure appears to provide the most viable technical route through addressing these identified limitations associated with single-mechanism approaches. Recent work has shown that there are synergistic effects from bacterial mineralisation combined with shape-memory fibre actuation in multi-functional healing matrices where the performance of the systems exceeds either mechanism acting alone, suggesting that a new generation of engineered materials with robust, multi-cycle healing capabilities for real infrastructure deployment may be around the corner [17]. By combining these embedded sensor networks and IoT data platforms with self-healing materials, the system advances the concept even further from passive material behaviour to an active monitored smart infrastructure reporting its own state and healing status in real-time.

Sustainability Summary In short, the reviewed lifecycle analyses are not surprising in that they consistently support the economic and environmental case for self-healing materials used in long-life infrastructure given sufficient initial material cost premiums can be accommodated within project financing frameworks with a preference for longer-term value. Lowest capital cost bid procurement models for infrastructure routinely discriminate against innovative materials that although more expensive to procure upfront have better lifecycle performance as measured by the net present value of total ownership costs over structural design life.

Future research should place priority on large-scale field demonstration projects capable of supplying long-term performance data in realistic service conditions across diverse climatic zones, loading regimes and structural typologies. That huge gap between proof-of-concept in the laboratory and engineering performance in the field continues to be the biggest barrier to adoption by conservative owners of these aging infrastructures, and their likewise conservative engineers. Pilot projects have reported encouraging initial results in the Netherlands (the self-healing asphalt trial on A58 motorway), Belgium (bacterial concrete application in bridge deck) and Japan (various SMA-embedded seismic wall systems); however these still necessitate long-term (> 10–20 years) monitoring programmes, just to deliver the performance datasets that structural engineers and regulatory authorities need prior to acceptance of new material types within national design codes. The key to unlocking in situ quantification of performance recovery through healing event detection will be investment into digital monitoring infrastructure, comprising embedded sensors, acoustic emission detection, fibre-optic strain gauges and data platforms such as those provided by IoT.

6. Conclusion

This review provides a global meta-analysis of self-healing smart materials for sustainable infrastructural development synthesising results from 214 primary studies published between the years 2005 and 2024 on all material platforms, including cementitious, polymeric, asphalt, ceramic and metallic. The meta-analysis establishes that the self-healing mechanisms, including microbial mineralisation, microencapsulation, vascular networks, reversible covalent chemistry and shape-memory actuation demonstrate a weighted mean healing efficiency of 78.3 % across material classes, which provides strong support for technical feasibility in white-box laboratory conditions. Self-healing materials are a highly sustainable solution that, according to lifecycle assessments conducted over 50-year service periods, should estimate reductions in carbon emissions of between 15% and 27%, along with maintenance cost savings of up to 50%. These numbers have an even stronger significance as global infrastructure commitments target net-zero emissions; building using circular economy principles;

But, despite those promising results, more critical analyses reveal that what has limited engineering confidence and constrained regulatory standardisation at mainstream scales is pervasive laboratory bias in results, inconsistency in reporting of heal efficiency with established conventions [the 'convention' being that healing efficiencies are usually not reported) and the absence of long-term performance metrics over multiple cycles. The most urgent needs of the field are: (i) international harmonisation of test standards for healing efficiency that allow comparison across laboratories and specification by regulators; (ii) large scale, long-term field demonstration projects with digital sensor monitoring to assess performance over a range of climatic and loading conditions; (iii) economic procurement frameworks that favour whole-life performance over initial capital cost allowing self-healing materials to compete on their intrinsic merits; and (iv) exploration into multi-mechanism hybrid systems capable of overcoming the single-cycle depletion/temperature-sensitivity limitations posed by uparalleled encapsulated or vascular technologies. In conclusion, these challenges can be systematically solved with coordinated academic, industrial and policy investment in self-healing smart materials a foundational technology for the sustainable built environment that promises to extend infrastructure lifespans, reduce embodied carbon and reinvent the economics of civil asset management for decades to come.

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