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REVIEW ARTICLE

Crack Repair Methods in Sustainable Building Structures: A Review

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ABSTRACT - Cracks in building structures are common due to environmental changes, material deterioration, and mechanical stress, but not always structurally significant. The objective of this review is to examine both conventional and emerging crack repair methods that enhance structural integrity while meeting sustainability goals. The study analyses established techniques such as epoxy resin injection and polyurethane grouting alongside innovative options including electrochemical mineral deposition and bacteria-based self-healing. A structured review approach was used to compare the mechanisms, environmental impact, and long-term performance of each method. The analysis also considered key factors influencing crack formation, including temperature fluctuation, moisture ingress, chemical reactions, and construction quality. Findings indicate that epoxy resin injection can restore up to 95% of compressive strength, while bio-based polyurethane and microbial self-healing approaches reduce carbon emissions by approximately 30-40% compared with conventional materials. Electrochemical deposition methods achieve up to 90% sealing efficiency when powered by renewable energy. These data highlight the strong potential of eco-efficient repair technologies to extend service life and improve structural resilience. The review concludes that integrating sustainable materials with modern monitoring tools supports durable and low-carbon construction. This work is relevant to engineers, researchers, and policymakers seeking practical, environmentally responsible solutions for long-term building maintenance.

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INTRODUCTION

Cracks in buildings are widespread problems that not only compromise structural integrity and durability but also threaten the safety and lifespan of both traditional and modern constructions [1]. These defects arise from a range of factors and can be attributed to the interactions among material limitations, environmental stressors, and human actions. They may also result from design misjudgements or ageing infrastructure. Although cracks are sometimes regarded as cosmetic issues, when left unaddressed, they can lead to structural failure, reduce load-carrying capacity, and accelerate deterioration [2]. Various crack patterns observed on building surfaces are shown in Figure 1. These cracks can indicate deeper structural or environmental problems, which is why early detection and proper repair methods are essential.

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Despite widespread adoption of green construction practices, the durability performance of sustainable structures often remains uncertain. Many eco-materials demonstrate reduced long-term strength or moisture resistance, leading to early cracking and repair cycles that offset their environmental gains. This gap between sustainability goals and structural durability forms the core problem addressed in this review. Sustainable building structures, with their focus on human well-being, energy efficiency, and reduced carbon footprint, have introduced a new era in modern construction. As the number of developments achieving Green Building Index (GBI) certification increases, they are also being recognised for their use of eco-materials, water- and energy-saving systems, and improved indoor environmental quality. The green building movement has expanded rapidly across Malaysia in recent years [3]. However, even in the most highly rated buildings, persistent cracking remains a pathway for long-term deterioration through moisture infiltration, potentially compromising structural capacity and sustainability performance [4-5]. Figures 2A and 2B show that current repair methods do not always provide the durability or strength demanded by today's sustainable construction practices. Figure 2A depicts a hairline fracture in a Platinum-rated building that reopened after several humidity cycles, while Figure 2B shows a larger crack in the same structure where epoxy injection failed to achieve full-depth penetration.

The objective of this paper is to critically review existing and emerging crack repair methods with respect to their structural efficiency, environmental performance, and applicability in sustainable construction. Specifically, the review aims to (i) identify the mechanisms causing cracks in green and conventional buildings, (ii) compare the effectiveness and ecological impact of major repair techniques, and (iii) highlight future directions for durable, low-carbon maintenance strategies. The presence of cracks in buildings (including sustainable or green structures) does not necessarily indicate poor design, poor construction, or non-compliance with certification requirements. Instead, it reflects the complex interplay between internal and external influences that affect even the most advanced engineering solutions. These influences include changing climatic conditions and the behaviour of natural materials. Some materials are inherently sensitive to their surroundings, such as concrete shrinkage during curing, rusting of steel in humid environments, and degradation of composites under UV exposure [2; 6]. These processes lead to the formation of micro-fissures that gradually expand under thermal stress, mechanical loads, or chemical reactions [5]. In addition, construction issues such as insufficient curing, poor compaction, and improper joint spacing create weak zones that accelerate crack formation [6-7].

Table 1 categorises concrete cracks by their formation mechanism, typical morphology, and detection method, helping establish a common vocabulary and highlight the multi-faceted challenges of crack remediation. This table classifies cracks by their dominant formation mechanism (primary cause), typical morphology and width, associated structural impact, and recommended detection method, rather than by orientation alone, to support engineering diagnosis and repair selection. In Malaysia, many public buildings develop cracking defects that range from minor surface fissures to deeper structural cracks; these problems are commonly associated with soil settlement, construction quality issues, and ageing materials, underscoring the need for robust rehabilitation and maintenance strategies [8]. Similar findings were reported in a case study of residential buildings near construction sites, where floor and wall cracks were linked to soil settlement rather than piling work, indicating design and site investigation issues [9]. Another study on health clinics in Johor and Negeri Sembilan found cracks to be among the most common defects, with environmental factors accelerating deterioration in several locations [10].

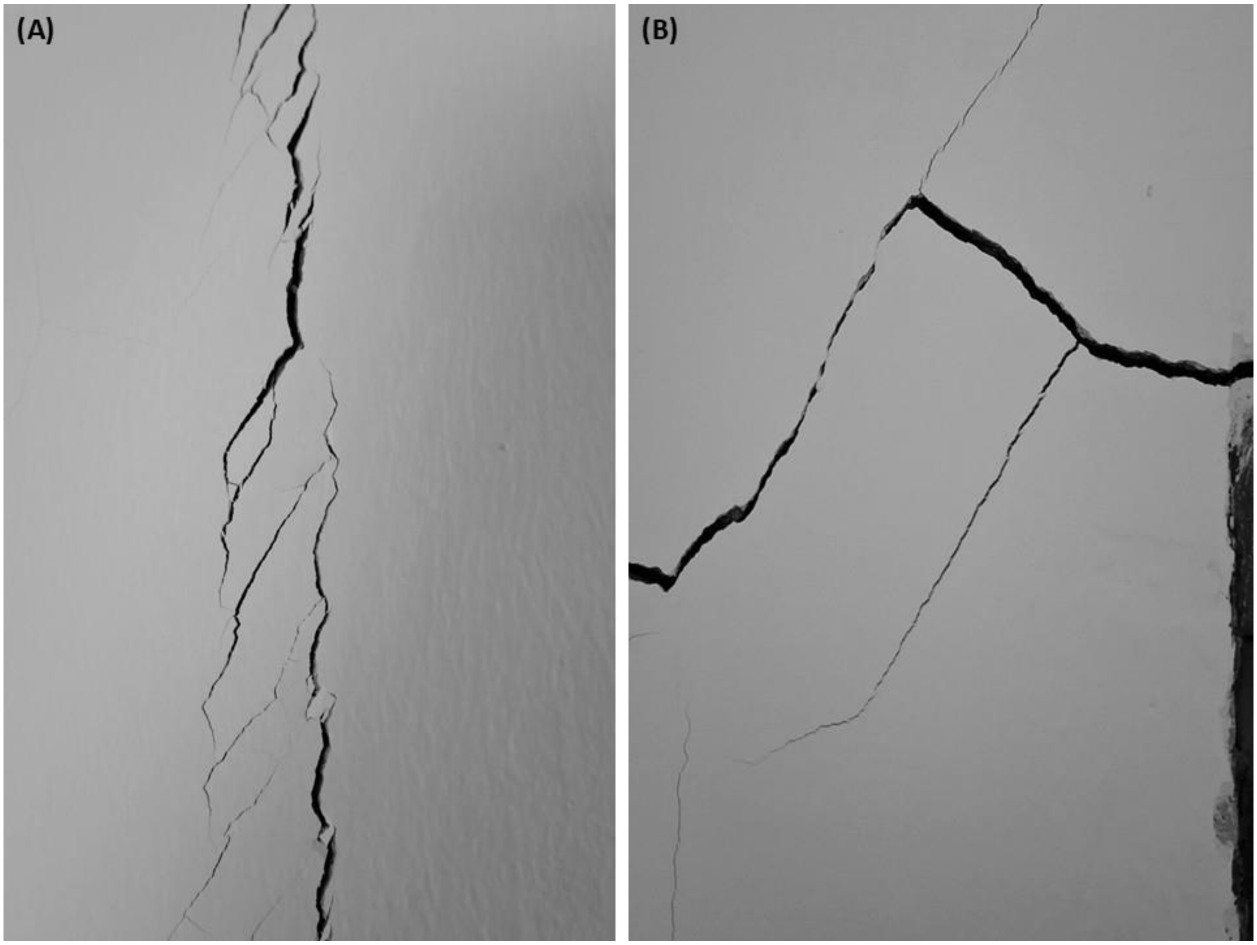


Figure 1. Examples of cracks in building surfaces: (A) Vertical cracking pattern on a wall surface, indicative of potential structural stress or material degradation. (B) Horizontal and diagonal cracking likely result from differential movement or environmental influences such as moisture ingress or temperature variation. These images underscore the importance of thorough assessment and repair strategies to maintain building integrity. The photographic examples illustrate common surface patterns, but Figure 1 is intended only as a visual aid; diagnosis should prioritise mechanism-based classification (see Table 1).

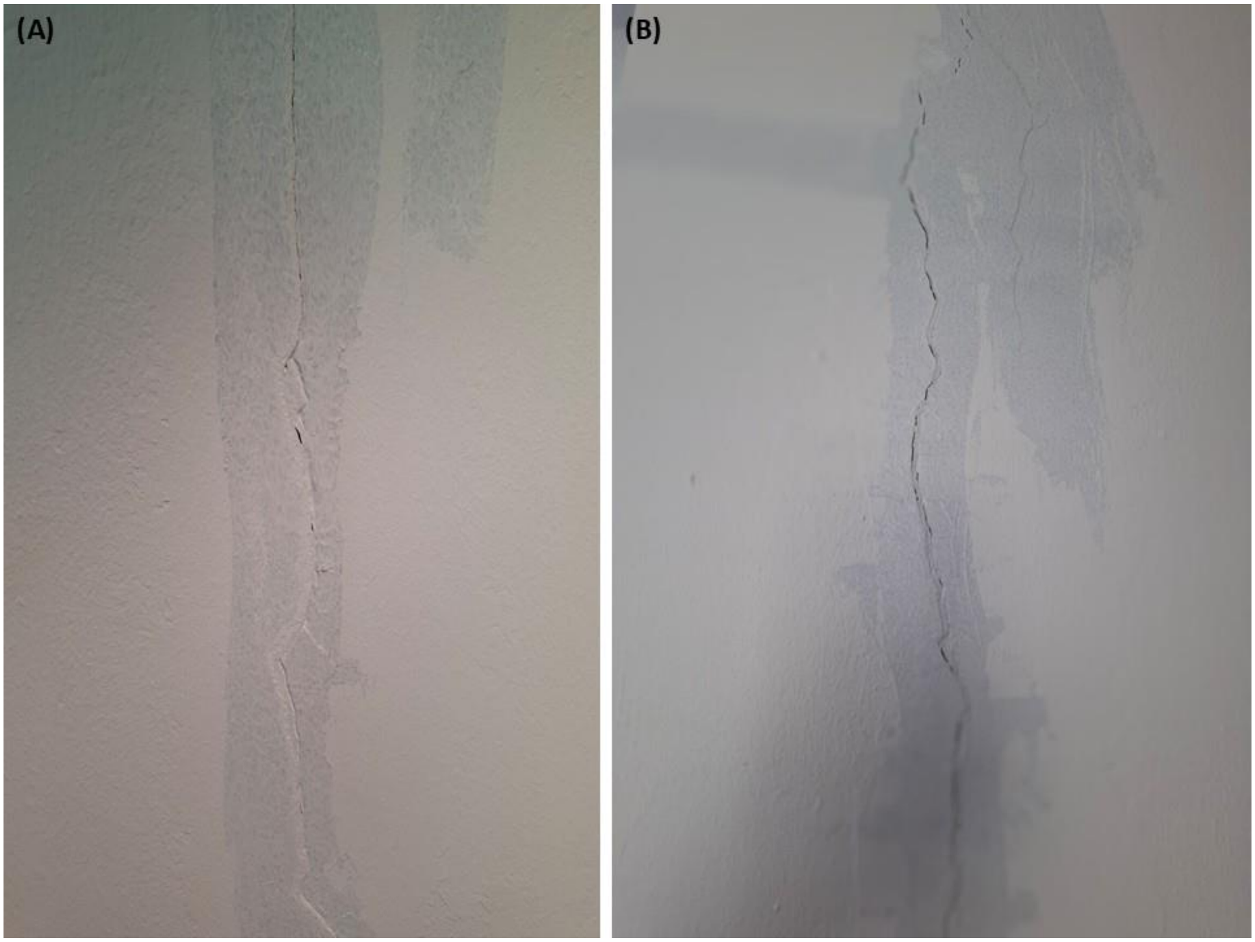


Figure 2. Examples of repair failures in a Platinum-rated sustainable building in Malaysia. (A) Hairline fracture in an office lobby patched with conventional filler, which reopened after seasonal humidity cycles; and (B) Larger fissure in a residential tower treated with a cementitious filler containing partial resin penetration, showing incomplete filling and persistent voids.

Table 1. Classification of Concrete Cracks by Mechanism, Morphology, and Detection Method

Crack Type/Mechanism	Typical Width (mm)	Common Causes	Typical Crack Pattern	Structural Impact	Detection Method	Reference
Plastic shrinkage	0.05-0.3	Rapid moisture loss during setting	Random pattern and spiderweb-like	Primarily cosmetic	Visual inspection	[11]
Drying shrinkage	0.1-0.5	Loss of capillary water over months	Parallel and map-pattern	Reduced durability and permeability	Crack tape measurement	[12]
Thermal stress	0.2-1.0	Daily or seasonal temperature swings	Wide opening, and isolated	Fatigue and surface spalling	Infrared thermography	[13]
Settlement or structural	0.5-5.0	Foundation movement and overload	Vertica or horizontal offsets	Severe and can lead to collapse	Light detection and ranging/ Digital image correlation	[14]

Alkali-silica reaction	0.1-0.3	Reactive aggregate and alkali moisture	Patterned 'map' cracks and gel bloom	Internal pressure, loss of strength	SEM, microscopy	[5]
Freeze-thaw	0.1-0.4	Water freezing in pores	Rough edges, granular surface	Surface scaling, spalling	Ultrasonic pulse velocity	[15]
Corrosion-induced	0.05-0.2	Steel rebar rust expansion	Rust staining, narrow linear	Loss of cover, reduced load capacity	Half-cell potential	[16]

Conventional repair techniques, such as epoxy injection and cement grouting, provide temporary fixes but do not address underlying causes or adapt well to modern materials [17]. Advanced composites and high-performance concrete exhibit unique fracture behaviours that require tailored solutions [18]. Furthermore, traditional methods rarely consider long-term environmental exposure, making structures vulnerable to recurring damage in freeze-thaw or seismic conditions. This paper reviews the causes of cracks and the repair methods available, describing recent innovations such as embedded sensors for in-situ monitoring and self-healing materials that extend structural lifespan. It also discusses the alignment of these technologies with broader sustainability goals. Persistent cracking in sustainable buildings highlights the need for repair approaches that restore both integrity and long-term environmental performance [1]. Since conventional solutions often provide only temporary relief, green-certified buildings demand more comprehensive strategies that minimise embodied carbon, preserve energy efficiency, and ensure life-cycle durability.

Unlike previous reviews that address crack repair purely from structural or materials viewpoints, this study integrates sustainability metrics such as embodied carbon, life-cycle impact, and renewable energy use into the evaluation framework, providing a holistic perspective on sustainable crack rehabilitation. This paper adopts a narrative review approach that thematically synthesises research published between 2018 and 2025 on crack repair technologies and sustainability performance. Rather than applying a rigid systematic protocol, the review integrates recent advances in materials, repair techniques, and monitoring innovations to highlight practical relevance and conceptual links between structural resilience and environmental responsibility. Particular attention is given to studies conducted in tropical regions, especially Malaysia, where climatic and material conditions present distinct challenges for achieving long-term building durability within sustainable construction frameworks.

CAUSATION OF CRACKS IN BUILDING STRUCTURES

One of the most common causes of cracks in buildings is overloading or foundation movement, such as differential settlement, which redistributes stress beyond the capacity of a material to bear its load [17]. During temperature fluctuations, materials expand and contract, generating thermal stress, one of the main non-structural causes of cracking that is expected to become more severe as temperature extremes increase [5]. The rising frequency of heavy rainfall and freeze-thaw cycles also contributes to moisture penetration, accelerating these processes. Materials can become completely or partially swollen, softened, or deteriorated by water and humidity. Curing- or heating-induced microstructural changes may create internal stresses even without overall volume change in the system. For instance, internal reactions such as the alkali–silica reaction or sulphate attack produce expansive compounds within the cement gel, generating internal pressure that accelerates cracking [14; 19]. Figure 3 presents an overview of various factors contributing to crack formation in buildings. This causation analysis provides the conceptual foundation for selecting appropriate repair techniques later discussed in Section 3.

The type and quality of materials used in construction also play a critical role. Problems such as low-grade aggregates, inadequate curing, or poor mix design, particularly when recycled materials with high porosity are involved, can lead to excessive shrinkage and particle deflocculation [1]. Therefore, the use of advanced admixtures (e.g., shrinkage-reducing compounds) and improved curing techniques is essential to control early-age cracking. The introduction of alternative materials such as recycled aggregates, slag, and fly ash is reshaping sustainable construction. However, these materials often behave differently during curing or under environmental stress, affecting shrinkage and cracking patterns [1; 20]. Table 2 summarises the key mechanisms responsible for concrete cracking due to environmental and material factors, along with the most effective mitigation measures.

Table 2. Causes of Cracks in Building Structures and Mitigation Strategies

Category	Cause	Effect on Cracking	Mitigation Strategies	Reference
Thermal Stress	Temperature fluctuations	Micro-crack initiation	Expansion joints, thermal breaks	[11]
Moisture Ingress	Freeze-thaw cycles, humidity	Pore pressure, matrix swelling	Waterproofing, drainage systems	[21]
Chemical Attack	Alkali-silica reaction	Expansive byproducts	Low-alkali cement, pozzolanic additives	[14]
Foundation Movement	Differential settlement	Structural cracks, shear failures	Soil stabilization, deeper footings	[1]
Material Incompatibility	Recycled aggregates	Early-age shrinkage	Compatibility testing, standardized mixes	[22]

Concrete incorporating slag may cure more slowly, increasing susceptibility to early-age cracking under load. Poor building practices can aggravate these problems. Inadequate compaction, improper reinforcement, and insufficient curing produce weak structural elements prone to cracking [23]. On-site modifications, such as over-watering mixes to improve ductility, can also compromise long-term durability. Other environmental and dynamic forces, including seismic activity, wind loading, and traffic-induced vibration, exert additional stresses on buildings [21]. These are particularly concerning for older structures where materials have degraded over time. Non-trivial ground settlement, often due to inadequate soil compaction or fluctuating groundwater levels, may cause further inhomogeneity, uneven load distribution, and ultimately cracking or even collapse [22].

Design flaws can also trigger cracks. Omitting expansion joints or miscalculating load paths can lead to stress concentrations [16]. Neglecting thermal expansion or local environmental conditions can shorten a building's lifespan. To prevent such issues, performance-based design validation and digital twin simulations should be incorporated at the design stage [15]. Material strength naturally declines over time, reducing a structure's ability to bear loads. Processes such as carbonation and reinforcement corrosion further accelerate deterioration, particularly in older concrete structures without modern protective measures [11]. Addressing these challenges requires an integrated approach that includes thorough geotechnical investigation, sound structural design, proper material selection, and continuous maintenance and monitoring. Such an approach is essential to ensure that both new and existing buildings remain robust while maintaining their sustainable function.

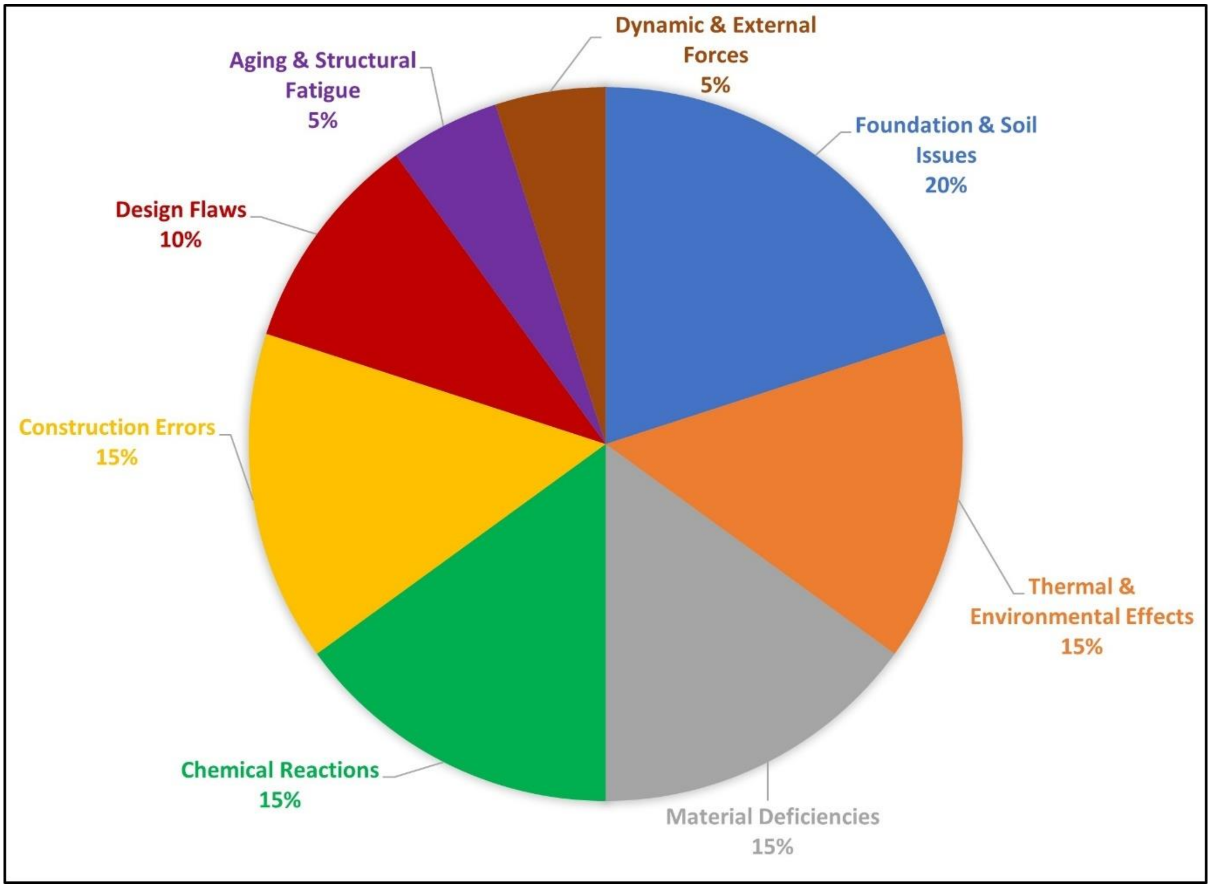


Figure 3: Causes of Crack Formation in Buildings. A visual representation of key factors that contribute to structural cracking. (Source: Author-generated based on compiled data and thematic synthesis of published studies on crack causation and repair from 2018 to 2025).

CRACK REPAIR METHODS

The choice of repair method plays a pivotal role in restoring structural performance while maintaining alignment with sustainable design principles. Inappropriate techniques can accelerate deterioration or increase the building's carbon footprint over its life cycle. The selection of rehabilitation measures for cracks in reinforced concrete structures should therefore consider the cause, width, and location of the cracks, as well as the structural function of the component involved [24]. Crack sealing is no longer viewed merely as an isolated maintenance activity but as part of a broader, long-term, and eco-efficient strategy aimed at optimising energy use, chemical consumption, and embodied carbon over a structure's service life [25]. The suitability of any repair method depends on crack morphology (width and depth), location within the structure, environmental exposure (for instance, chloride-rich or freeze-thaw conditions), and compatibility with the existing substrate to ensure durable adhesion and mechanical integrity [26]. Table 3 summarises these options to assist in selecting sustainable repair approaches. Figure 4 illustrates the wide range of available techniques, from conventional resin injection to innovative self-healing materials using bio-based constituents. The following subsections describe key conventional and emerging techniques, highlighting their mechanical performance, environmental implications, and relevance to sustainable construction. Figure 4 and Table 3 summarize the key repair strategies to minimize textual repetition.

Epoxy Resin Injection

Epoxy resin injection remains a fundamental method for repairing inactive or narrow cracks (< 0.05 mm) [27]. The technique begins with thorough crack cleaning using pressurised air or vacuum to remove laitance and dust that could impede resin penetration [28]. A mildly thixotropic epoxy system—becoming less viscous under shear enhances microcrack penetration, enabling refusion of fracture planes and recovery of near-original strength while providing waterproofing [29]. Hybrid systems combining epoxy with hydrophobic coatings (such as silane-siloxane) form protective barriers that resist chloride ingress and moisture, making them suitable for coastal or freeze-thaw environments [30]. Deep resin infiltration produces a thin polymer film along the crack surface, improving flexural strength (up to 4.08 MPa) and increasing compressive strength by 20-30 % [31]. It also mitigates drying shrinkage and interfacial shear stresses by strengthening the pore network. Traditional epoxies contain bisphenol A, a petrochemical precursor with a high carbon footprint [27]. Bio-based epoxies derived from renewable sources such as linseed oil or lignin, a by-product of the paper industry, achieve comparable tensile strengths (35-40 MPa) while reducing life-cycle carbon emissions by 30-40 % [32-33]. Challenges remain in large-scale production and ensuring compatibility with existing construction practices, yet such materials mark a significant step toward low-impact repair. Recent nano-encapsulation technologies embed epoxy precursors in silica nanoparticles for slow release and autonomous self-sealing upon crack activation, potentially extending maintenance intervals by 30 %. While epoxy systems continue to dominate structural crack repair, their environmental drawbacks have prompted growing interest in greener electrochemical and bio-based alternatives, discussed next.

Electrochemical Deposition Method (EDM)

In the electrochemical deposition method, electrolysis promotes the formation of calcium carbonate ($CaCO_3$) within cracks in submerged or reinforced concrete [34]. The process involves polarising the steel reinforcement as the anode and placing an external electrode as the cathode in an electrolyte solution such as $Ca(NO_3)_2$. Calcium and carbonate ions migrate into cracks, where they precipitate to form sealing crystals [35]. Pulse-current systems that alternate between high and low voltage stages counter electrode polarisation and enhance ion mobility, achieving up to 90 % sealing efficiency in tidal and marine environments [36; 37]. Solar-assisted EDM systems powered by photovoltaic panels and battery storage can lower greenhouse-gas emissions by about 70 %, enabling sustainable off-grid applications in bridges and offshore platforms [38]. The main limitations include difficulty in controlling current density (typically 0.5–1.5 A m^{-2}) to avoid steel corrosion and the need to optimise electrolyte composition for various concrete types [39]. Recent impedance-guided adaptive pulse-width modulation techniques enable real-time control of current distribution, ensuring uniform deposition even in heterogeneous substrates [36]. Long-term monitoring of a five-year marine pilot project confirmed chloride diffusion reductions above 60 %, demonstrating the durability of EDM under aggressive exposure [34]. Although EDM offers a promising low-carbon alternative for marine structures, further optimisation of current control and electrolyte chemistry is required for widespread adoption.

Bacteria-Based Self-Healing

Microbial-induced carbonate precipitation (MICP) represents a breakthrough in autonomous crack repair, particularly for hairline cracks. Ureolytic bacteria such as *Bacillus subtilis* and *Sporosarcina pasteurii* metabolise urea through enzymatic hydrolysis, generating carbonate (CO_3^{2-}) and ammonium (NH_4^+) ions when calcium ions (Ca^{2+}) are available [40; 41]. The reaction precipitates $CaCO_3$ (calcite, vaterite, or aragonite) on crack surfaces, effectively sealing and strengthening the matrix [42]. In practice, the microbes are embedded within the concrete or encapsulated in carriers and become active upon water ingress [25]. Encapsulation materials such as porous silica gels, hydrogels, and polyurethane microcapsules protect spores from mechanical and moisture stress during mixing and curing [43-44].

These carriers also enable delayed activation spores remain dormant until triggered by environmental cues such as pH change or moisture infiltration. Laboratory studies show that such systems can achieve over 90 % crack closure, improve durability, and reduce maintenance needs [42]. Recent developments include zeolite-based carriers with high nutrient capacity to sustain bacterial activity in high-pH concrete (pH > 12) [17]. Field trials in sewer tunnels demonstrate effective sealing of cracks up to 3 mm when MICP is combined with enzymatic nitrate-reduction pathways [45]. Incorporating recycled fillers such as finely ground glass enhances composite deformability and toughness in MICP-treated concretes [46]. Synthetic-biology approaches have produced engineered microbial consortia capable of both $CaCO_3$ precipitation and heavy-metal immobilisation, expanding MICP's potential for infrastructure in contaminated environments [47]. Despite its strong environmental promise, large-scale deployment of MICP still faces challenges in cost reduction, bacterial viability, and performance consistency under extreme pH or temperature conditions.

Polyurethane Grouting

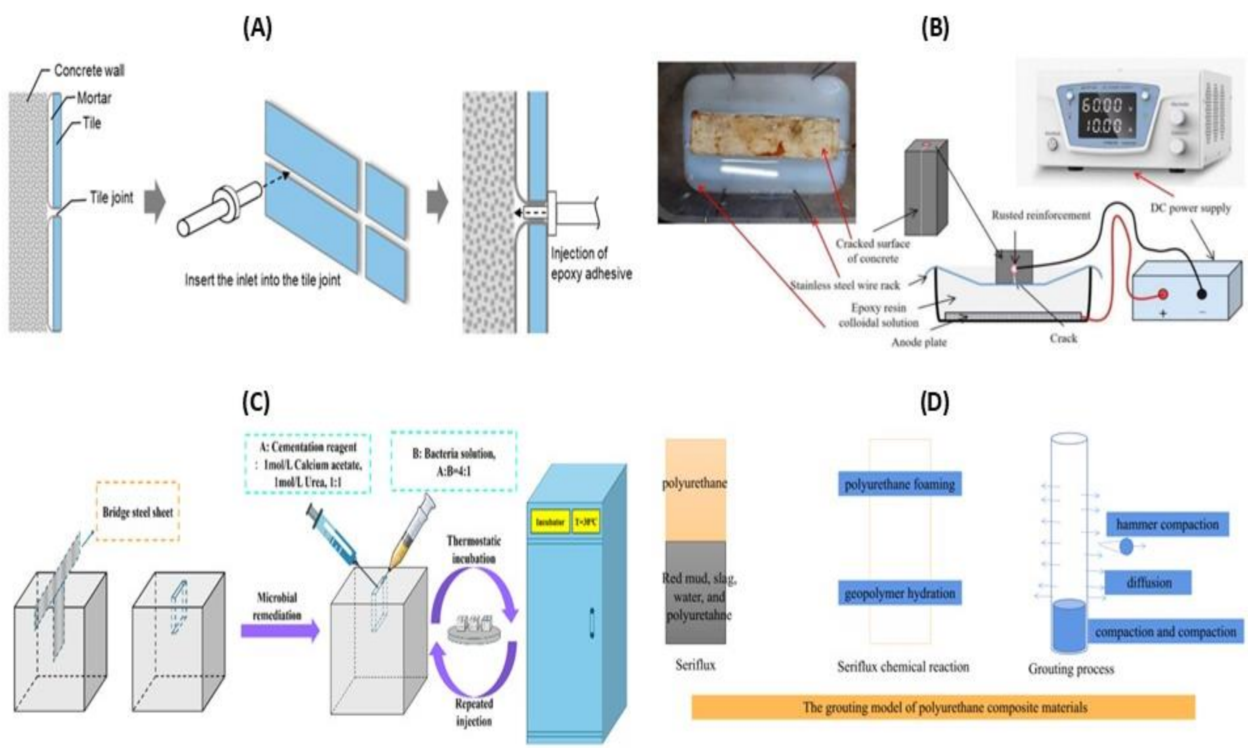
The compatibility and durability of polymer-based sealants are essential for sustaining the long-term performance of repaired structures [26]. Polyurethane (PU) grouts expand when in contact with water, producing flexible foams that seal dynamic cracks in water-bearing structures [48]. Their rapid expansion makes them effective for leak sealing, but also introduces sustainability concerns because conventional PU relies on petrochemical isocyanates that are energy-intensive to manufacture [49]. Bio-based PU grouts synthesised from castor oil or algae reduce embodied carbon by roughly 60 % while maintaining comparable shear strength to conventional PU [34]. Outdoor performance is limited mainly by UV degradation, which can be mitigated through the addition of free-radical scavengers such as hindered amine light stabilisers, thereby extending service life [50]. Bio-PU generally cures more slowly (20-30 min compared with 5-10 min for synthetic PU), requiring formulation adjustment [51]. Innovations include incorporating nanocellulose fibres into the foam matrix to enhance mechanical strength and introduce partial biodegradability at end-of-life. The emergence of 3D-foam printing enables in-situ injection into complex voids, reducing material waste and on-site handling [48]. Hybrid systems combining PU with silica fume or nano-silica improve chemical resistance and dimensional stability in corrosive environments. Robotic-assisted grouting technologies are now being developed to automate crack injection in confined areas, improving worker safety and ensuring uniform material distribution.

Fiber-Reinforced Crack Bridging

Fibre-reinforced polymer (FRP) systems, typically using carbon, basalt, steel, or natural fibres, are widely used for structural retrofitting to redistribute loads across cracks [52]. Bonding or anchoring high-strength fibres over a crack restores flexural strength, increases toughness, and prevents further propagation [53]. Sustainable variants employ bio-based matrices, such as flaxseed-derived epoxy modified with linolenic acid glycidyl esters, which provide reversible bonds for recyclability. Thermal treatment at 300 °C degrades the resin and allows up to 95 % fibre recovery [50]. Pre-encapsulated FRP strips with self-adhesive bonds can be installed in less than two hours, reducing downtime. Advanced FRPs integrate self-sensing capability through embedded carbon nanotubes that monitor crack development via electrical-resistivity changes [50]. Diels-Alder-based bio-resin matrices enable reversible cross-linking, allowing full recycling of composite materials after service life [54]. Embedding fibre-Bragg-grating sensors provides simultaneous measurement of strain and temperature for comprehensive structural-health monitoring. Other innovations include magnetically responsive fibres that can be repositioned after installation to adjust load paths and bio-inspired fibre architectures that mimic shell structures for improved toughness and damage tolerance. FRP systems, therefore, represent a versatile and increasingly sustainable class of materials that combine structural reinforcement, durability, and integrated monitoring to extend building service life.

Table 3. Comparative Overview of Crack-Repair Techniques

Method	Crack Type	Crack Width Range	Strength Recovery	Permeability Reduction	Hardness Gain	Environmental Impact	References
Epoxy Resin Injection	Static hairline fissures	Extremely fine cracks	Near-complete restoration	Almost complete sealing	Not applicable	Moderate; petrochemical-based resin	[30; 33]
Electrochemical Deposition	Reinforcement embedded microcracks	Narrow to fine cracks	Good restoration	High reduction	Not applicable	Low; can be powered by renewables	[35; 38]
Bacteria-Based Self-Healing	Hairline to micro-cracks	Very fine cracks	Moderate restoration	Moderate reduction	Noticeable increase	Low- and moderate-use biodegradable by-products	[17; 25]
Polyurethane Grouting	Water-bearing, dynamic fissures	Moderate to wide openings	High restoration	Very high reduction	Not applicable	Moderate; bio-PU variants available	[48; 49]
Fiber-Reinforced Bridging	Structural offset and movement	Wider structural cracks	Strong recovery	Not applicable	Not applicable	Low; recyclable fibre components	[50; 54]



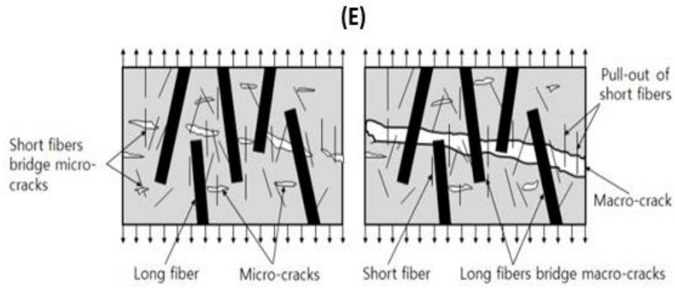


Figure 4. Schematic overview of common concrete crack-repair methods: (A) Epoxy resin injection for crack reinforcement (adapted from [31]); (B) Electrochemical deposition repair process (adapted from [34]); (C) Bacteria-based self-healing mechanism using *Sporosarcina pasteurii* (adapted from [21]); (D) Polyurethane grouting model for wide-fissure sealing (adapted from [48]); and (E) Fiber-reinforced bridging process for structural crack stabilization (adapted from [30]). (The Creative Commons Attribution (CC BY 4.0) license (http://creativecommons.org/licenses/by/4.0/)).

CHALLENGES AFFECTING BUILDING STRUCTURE SUSTAINABILITY

The sustainability of building structures depends on overcoming a range of material, environmental, and managerial challenges that affect both new and existing constructions. These challenges directly influence durability, service life, and the environmental performance of built assets, as illustrated in Figure 5. The following subsections outline the major factors limiting sustainable structural performance and propose strategies to mitigate them.

Material Selection and Compatibility

The use of sustainable materials such as recycled concrete aggregates (RCAs) and fly ash introduces additional uncertainty and complexity in predicting the behaviour of structural elements [55]. RCAs often contain residual mortar that weakens the interfacial transition zone, reducing bond strength by approximately 30% compared with natural aggregates [56]. Hybrid constructions, such as timber-concrete composites, are particularly prone to differential thermal expansion [57]. Wood swells while concrete expands, leading to microcracks at junctions during temperature fluctuations [22]. Nanomaterial enhancements, such as carbon nanotubes that improve tensile strength and graphene oxide coatings that boost corrosion resistance, can mitigate cracking but rarely eliminate sub-millimetre openings [58]. Interestingly, these microcracks (0.1-0.3 mm) fall within the optimal range for biomineralization, allowing targeted mineral bridging in engineered composites. However, inconsistent supply chains and limited traceability of recycled materials restrict quality assurance, posing challenges to achieving circularity and performance consistency.

Design and Construction Practices

Modern systems such as green roofs, kinetic façades, and modular assemblies introduce new stress patterns that may intensify cracking [59]. Inadequate drainage on green roofs, for instance, can increase slab deflection by over 12%, accelerating tensile crack growth [22]. Prefabricated modules often exhibit weak panel-to-panel connections, where gaps may exceed 0.5 mm [37]. Advanced design solutions, such as topology-optimized 3D printing and shape-memory alloy fasteners, help reduce stress concentrations and joint failures by about 25%. However, complex façade geometries and unreinforced openings frequently generate shear and edge cracks due to stress concentration [59]. High initial costs and limited access to green financing further discourage the adoption of sustainable innovations. Moreover, inconsistent building codes without clear embodied-carbon benchmarks create compliance uncertainty, hindering holistic, sustainability-driven design.

Environmental Factors Influencing Crack Formation

Environmental stresses and chemical exposure significantly influence crack development, particularly in structures using sustainable materials [60]. In arid regions, large diurnal temperature swings (up to 30 °C) can trigger thermal fatigue, widening cracks at 0.2-0.5 mm per year and degrading bio-based binders [61]. Urban heat islands amplify this problem, increasing the need for expansion joints to accommodate thermal movement. Freeze-thaw cycles can accelerate crack propagation by up to 20%, often eroding protective coatings on recycled aggregate mixes [19]. Chemical pollutants, including SO_2, react with calcium hydroxide to form expansive gypsum, compromising low-carbon cement systems [19]. In flood-prone zones, swelling clay soils can cause shear cracks at the slab-soil interface, endangering modular foundations [5]. In coastal or high-UV environments, polymeric sealants degrade faster, while salt crystallization exacerbates microcracking in high-fly-ash concretes. The lack of long-term life cycle data for novel bio-binders adds further uncertainty to predicting environmental durability under climate-induced stress.

Construction Quality and Remediation Techniques

Early-life distress in green buildings often stems from poor curing, inadequate compaction, or delayed crack detection. In recycled aggregate concrete, insufficient compaction can reduce design strength by up to 30%, promoting undetectable microcracks [62]. Advanced diagnostic tools, such as LiDAR-enabled digital twins, can now identify sub-millimetre cracks in real time, while lignin-based bio-sealants effectively repair hairline cracks and reduce volatile organic compound emissions by 70% [63]. Emerging technologies include piezoelectric sensors for early crack warnings and targeted carbon-fibre wraps for localized reinforcement [64]. However, natural and low-carbon construction systems, such as rammed-earth and straw-bale walls, require precise moisture control during assembly to prevent shrinkage and cracking [65]. A shortage of skilled green-construction workers increases the risk of improper installation and reduced system longevity. Moreover, while digital-twin platforms enhance predictive maintenance, their growing reliance introduces concerns about cybersecurity and interoperability that may compromise reliable monitoring if not addressed.

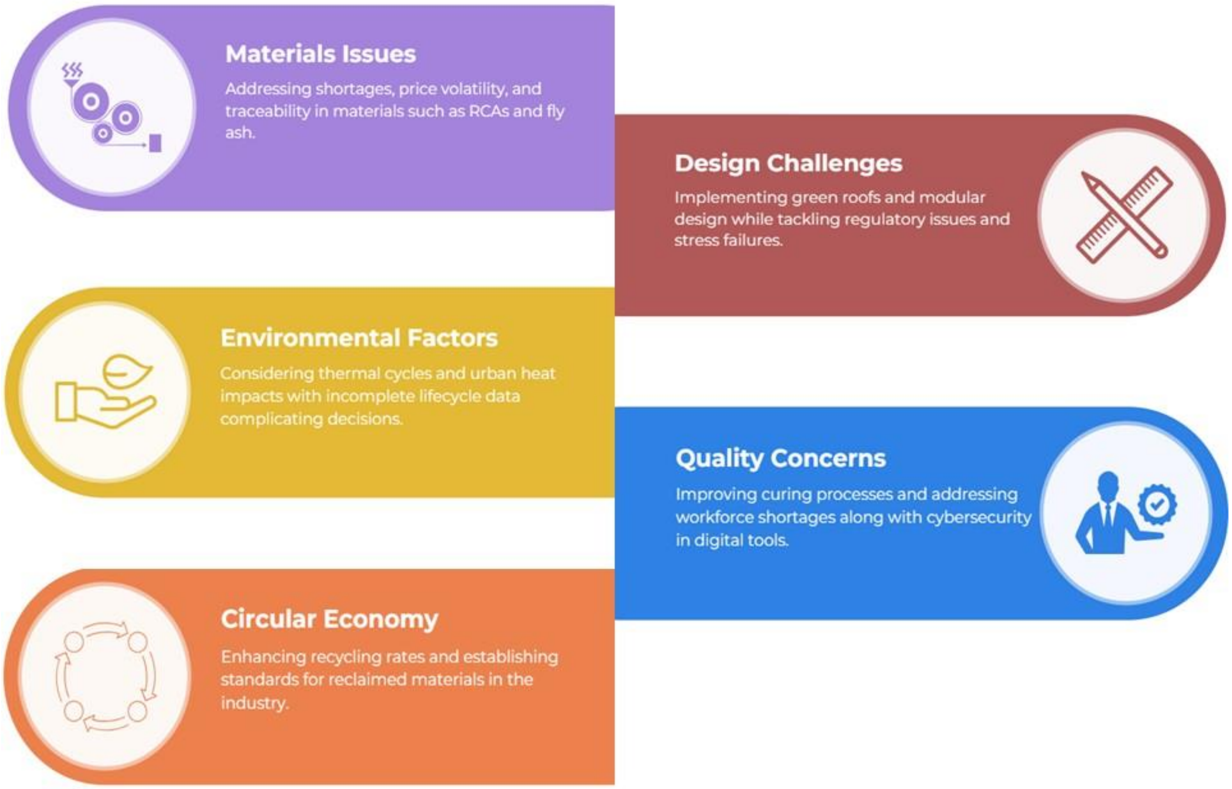


Figure 5. Chart illustrating the key challenges affecting building structure sustainability, including material selection, design and construction practices, environmental influences, and construction quality. Each factor contributes to crack formation and structural degradation, highlighting the need for integrated remediation and smart monitoring solutions. (Source: Author-generated based on thematic analysis of published reports and studies related to sustainable construction and durability from 2018 to 2025).

PERSPECTIVE ON MONITORING, EVALUATION, AND BUILDING SUSTAINABILITY

Proactive structural health monitoring (SHM) is vital for achieving sustainable infrastructure longevity and aligns closely with Malaysia's GBI objectives. SHM provides a critical bridge between structural performance and environmental stewardship, particularly in addressing recurring repair failures in even high-rated buildings. Non-destructive techniques (NDTs) such as acoustic emission monitoring can detect micro-fractures [66], triggering timely interventions such as epoxy injection or the use of biodegradable self-healing systems. Infrared thermography identifies moisture-induced delamination, guiding appropriate selection between electrochemical deposition for corrosion repair and polyurethane grouting for waterproofing [67]. Digital image correlation (DIC) accurately measures crack widths and displacements, supporting the choice between fibre-based bridging or microbial self-healing concrete [68]. Figure 6 contextualises advanced monitoring systems, showing that drone-based LiDAR offers 40% lower emissions compared with traditional scaffolding inspections, an outcome consistent with green building principles. AI-driven predictive models and digital-twin simulations are increasingly used to compare post-repair performance, such as stiffness recovery in resin-injected concrete versus microbial healing efficiency [69].

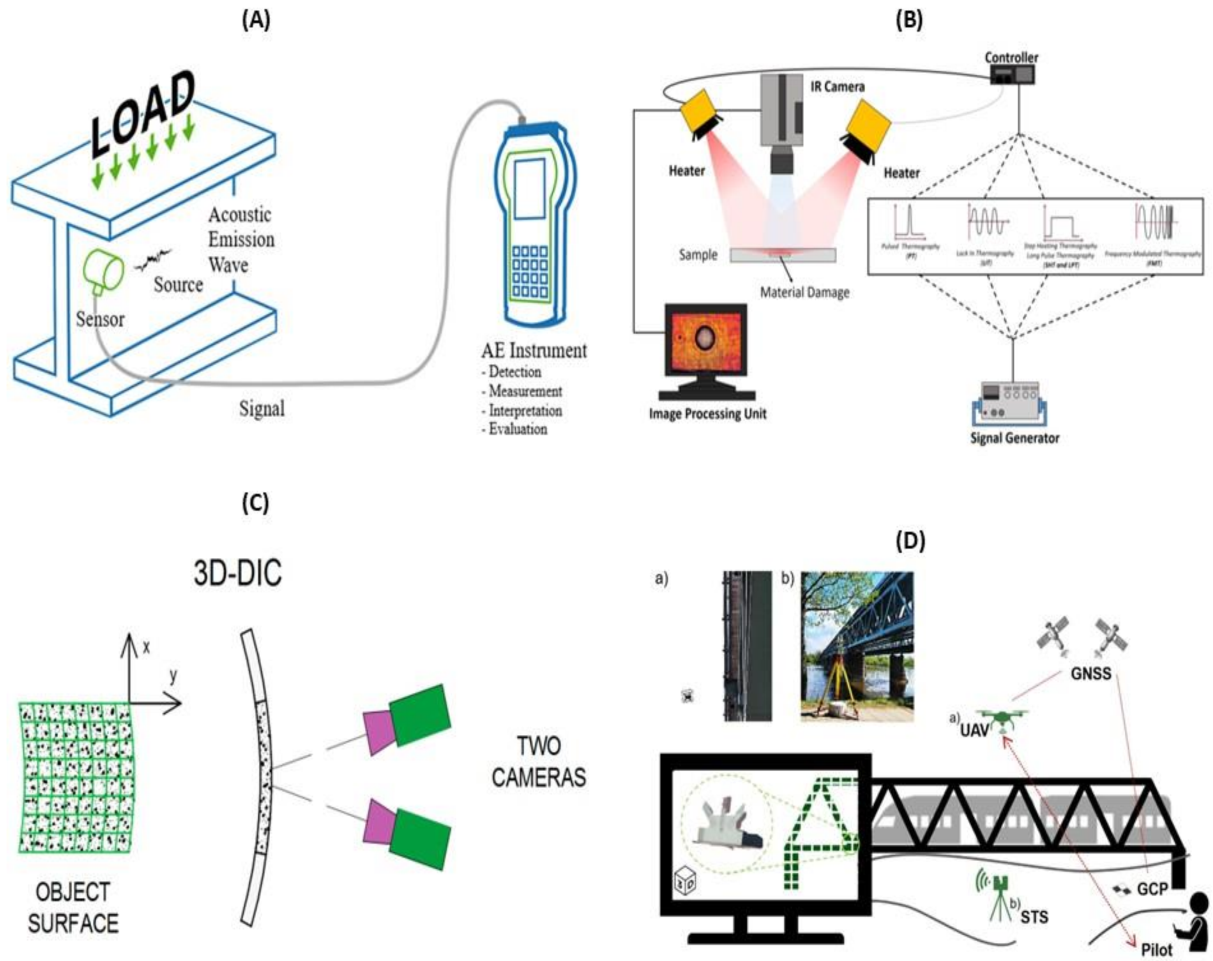


Figure 6. Schematic of advanced monitoring methods for concrete crack evaluation. (A) Acoustic Emission sensors for monitoring stress waves from microcracks for real-time damage assessment (adapted from [66]); (B) Infrared Thermography to inspect thermal anomalies due to moisture or delamination (adapted from [67]); (C) 3D-DIC for measuring surface strain and crack displacement (adapted from [68]); (D) UAV-based photogrammetry for large-scale crack mapping and monitoring structural deterioration (adapted from [69]).

Life cycle assessment (LCA) provides a crucial lens for evaluating sustainability trade-offs across different crack repair methods. Epoxy resins, for example, achieve rapid strength recovery but emit approximately 15-20 kg CO_2 per kg produced [27,31], a concern in humid tropical climates like Malaysia. Polyurethane grouting generates 10-12 kg CO_2 per litre and faces UV degradation, requiring stabilisers for tropical durability [48]. In contrast, self-healing bioconcrete reduces emissions by around 30% [42], though standardised microbial encapsulation techniques are still needed for consistent performance in high-humidity regions such as Sarawak. Moreover, indirect benefits, such as a 12% reduction in building energy use after leak remediation, should be integrated into Malaysia's GBI assessment criteria to better reflect repair-related sustainability gains.

Technical progress must be accompanied by adaptive policy frameworks. Current sustainability certifications like GBI seldom recognise emerging repair methods such as electrochemical deposition or carbon-fibre retrofitting, despite their proven environmental and structural advantages. Expanding certification coverage to include these methods would accelerate adoption, especially within public institutional buildings frequently affected by cracking. AI-enhanced SHM systems now achieve prediction accuracies of up to 90%, reducing maintenance costs in polycrack-prone facilities such as health clinics in Johor and Negeri Sembilan [10]. Emerging self-sensing sensors and ureolytic microbial systems hold promise for bioconcrete repairs but require climate-specific standards to ensure scalability in Malaysia's tropical conditions. Addressing these gaps demands a multidisciplinary effort linking materials science, biotechnology, civil engineering, and circular economy models. Integrating SHM and LCA findings into policy and practice will ensure that repair strategies not only extend structural durability but also uphold Malaysia's commitment to sustainable infrastructure and resilience against humidity cycles and thermal stress.

RECOMMENDATIONS FOR PRACTICE

Effective crack control in sustainable buildings depends on both preventive and adaptive strategies implemented throughout the building life cycle. Preventive measures should begin at the design stage, where performance-based simulations and digital modelling anticipate early-age shrinkage, thermal stress concentrations, and differential movement, particularly in hybrid systems such as timber-concrete composites. Research shows that proper joint detailing and compatibility assessments can significantly reduce microcracking caused by contrasting thermal expansion behaviours between materials like glulam and lightweight concrete [57]. Integrating these insights into Malaysia's green building frameworks can prevent crack initiation before construction even begins.

From a material perspective, repair compounds and sealants must balance mechanical performance with environmental responsibility. Bio-based alternatives offer a viable route forward: bio-oil-derived epoxy resins provide tensile strengths comparable to conventional epoxies while reducing embodied carbon by 30-40% [32-33]. Life cycle analyses of bio-based structural adhesives report up to 70% lower global warming potential than petroleum-based epoxy systems without compromising structural integrity [70]. Likewise, bio-polyurethane grouts from castor oil reduce embodied emissions by as much as 60% [17]. In Malaysia's humid and coastal zones, self-healing systems such as microbial-induced carbonate precipitation (MICP) and electrochemical deposition have achieved over 90% crack closure in laboratory tests and maintained more than 60% chloride diffusion reduction in long-term field trials [34; 43; 44]. Monitoring and maintenance should evolve from reactive to proactive. Advanced SHM technologies, including acoustic emission sensors, infrared thermography, and digital image correlation, enable the detection of microcracks before visible deterioration occurs [67–69]. When integrated with digital twin platforms and life cycle assessment tools, these systems allow timely intervention, maximizing structural benefit while minimizing environmental impact [64].

In Malaysia's tropical climate, where humidity, thermal cycling, and rainfall accelerate crack propagation, the combination of smart monitoring, low-carbon repair materials, and design-stage mitigation offers the most sustainable pathway to durable infrastructure. Yet technology alone is not sufficient. Field observations from Johor and Negeri Sembilan showed that poor workmanship and limited awareness remain major barriers to effective crack management [14;16]. Capacity-building programs in bio-based repair applications, SHM interpretation, and sustainable detailing are therefore critical for turning innovation into practice. Together, these measures, design-stage prevention, sustainable material selection, predictive monitoring, and professional training form a practical framework to ensure that crack management in tropical buildings enhances both structural durability and environmental performance, supporting Malaysia's GBI and wider sustainability objectives.

CONCLUSION

Crack repair in sustainable buildings represents a vital intersection between structural resilience, environmental responsibility, and technological advancement. While conventional repair techniques, such as epoxy resin injection and electrochemical deposition, remain effective for short-term strength recovery, they carry drawbacks including high embodied CO_2 (up to 15-20 kg CO_2/kg epoxy) and limited long-term compatibility with eco-materials. This reinforces the need for innovative solutions aligned with global and national sustainability goals. Emerging approaches such as bacteria-induced self-healing concrete, bio-based polyurethane grouting, and fibre-reinforced bridging systems offer measurable sustainability benefits. Studies show that bio-epoxy and bio-PU grouts can reduce life cycle carbon emissions by 30-60%, while microbial self-healing concretes achieve over 90% crack closure efficiency and extend service life by 20-40% under humid tropical conditions. Likewise, integrating carbon or basalt fibre systems enhances load redistribution and improves post-repair flexural strength by 25-30%, contributing to longer maintenance intervals and reduced resource use. These innovations not only address the root causes of cracking but also align with Malaysia's GBI framework, supporting the shift toward low-carbon, long-life infrastructure.

Achieving true sustainability in crack rehabilitation requires an interdisciplinary strategy that merges material science, biotechnology, robotics, and circular economy principles. Future research should focus on large-scale field validation of bio-concretes in high-humidity regions, the development of renewable-energy-powered SHM systems, and recyclable composite materials. Ultimately, sustainable crack repair must evolve from isolated interventions into an integrated life cycle approach that couples structural durability with environmental stewardship. Through a convergence of advanced technologies, informed policy, and ecological awareness, the construction industry can create buildings capable of enduring both climatic and human pressures, leaving behind a built environment that is stronger, cleaner, and more sustainable for generations to come.

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AUTHOR CONTRIBUTIONS

A.I.O.: Conceptualization, Methodology, Investigation, Writing - Original Draft, Visualization. A.B.L.: Funding Acquisition, Validation, Writing - Review & Editing. M.O.E.B.S. and L.S.W.: Formal Analysis, Data Curation, Writing - Review & Editing. C.S.W., Q.A.B.S., A.H.H.M., and A.O.V.: Formal Analysis, Resources, and Writing - Review & Editing. All authors have read and agreed to the final version of the manuscript.

DECLARATION OF AI USE

The authors declare that ChatGPT (OpenAI, GPT-5) was used to assist in language refinement, grammar correction, and formatting consistency. The tool was not used for data analysis, interpretation, or the generation of original scientific content. All substantive ideas, results, and conclusions are the authors' own.

DATA AVAILABILITY STATEMENT

Not applicable.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

REFERENCES

[1] Zhang, L. V., Marani, A., and M. L. Nehdi. (2022). Chemistry-informed machine learning prediction of compressive strength for alkali-activated materials. *Constr. Build. Mater.*, vol. 316: 126103. doi: 10.1016/j.conbuildmat.2021.126103.

[2] Velumani, P., Mukilan, K., Varun, G., Divakar, S., Muhil Doss, R., and P. Ganeshkumar. (2020). Analysis of cracks in structures and buildings. In *Journal of Physics: Conference Series*, vol. 1706: 012116. IOP Publishing.

[3] Yadegaridehkordi, E., Hourmand, M., Nilashi, M., Alsolami, E., Samad, S., Mahmoud, M., Alarood, A. A., Zainol, A., Majeed, H. D., and L. Shuib. (2020). Assessment of sustainability indicators for green building manufacturing using fuzzy multi-criteria decision making approach. *J. Clean. Prod.*, vol. 277: 122905. doi: 10.1016/j.jclepro.2020.122905.

[4] Sun, X., Miao, L., Wu, L., and H. Wang. (2021). Theoretical quantification for cracks repair based on microbially induced carbonate precipitation (MICP) method. *Cem. Concr. Compos.*, vol. 118: 103950. doi: 10.1016/j.cemconcomp.2021.103950.

[5] Golewski, G. L. (2023). The phenomenon of cracking in cement concretes and reinforced concrete structures: The mechanism of cracks formation, causes of their initiation, types and places of occurrence, and methods of detection-A review. *Buildings*, vol. 13 (no. 3): pp. 765. doi: 10.3390/buildings13030765.

[6] Su, Z., Zhou, F., Liang, J., Liu, A., Wang, J., Liang, J., Chen, B., and J. Yang. (2024). Fractal theory based identification model for surface crack of building structures. *Eng. Struct.*, vol. 305: 117708. doi: 10.1016/j.engstruct.2024.117708.

[7] Chen, H., Wu, Z., and R. C. Yu. (2025). Simulation of mixed mode I-II fatigue crack propagation in concrete with different strengths. *Theor. Appl. Fract. Mech.*, vol. 135: 104779. doi: 10.1016/j.tafmec.2024.104779.

[8] Mohd. Ashraf., Mohd. Nikmat, N. S. F. (2023). Common defects in public institutional buildings in Malaysia. *J. Sustain. Sci. Manag.*, vol. 18: pp. 36-53. doi: 10.46754/jssm.2023.07.003.

[9] Jamaluddin, N., Yeoh, D., Abdul Ghani, A. H., Boon, K. H., Ayob, S. S., Ibrahim, M. H. W., Mohamad, N., Chik, T. N. T., and N. H. A. Ghafar. (2018). A case study of residential buildings subjected to cracking failures. *Int. J. Integr. Eng.*, vol. 10 (no. 2): pp. 118-122. doi: 10.30880/ijie.2018.10.02.022.

[10] Apzan, N. S. M., Azuar, N. A. M. F., and H. Mohammad. (2022). Investigation of building crack on government health clinics in Johor and Negeri Sembilan. *Multidiscip. Appl. Res. Innov.*, vol. 3 (no. 1): pp. 247-256. doi: 10.30880/mari.2022.03.01.030.

[11] Cui, P., and Y. Qin. (2024). Introducing methods for analyzing and detecting concrete cracks at the No. 3 Huaiyin pumping station in the South-to-North water diversion project in China. *Buildings*, vol. 14.

[12] Hoa, N. T. T., Asamoto, S., and N. T. Lam. (2025). Experimental studies and prediction models for drying shrinkage of concrete in natural conditions. In R. Siddique, M. Soutsos, J. Li, T.-P. Huynh, and T. Ngo (Eds.), *Book Title Missing* (pp. 178-190). Springer Nature Singapore, Singapore.

[13] Yang, Y., Yao, J., Liu, J., Kong, D., Gu, C., and L. Wang. (2024). Evaluation of the thermal and shrinkage stresses in restrained concrete: New method of investigation. *Constr. Build. Mater.*, vol. 411: 134493. doi: 10.1016/j.conbuildmat.2023.134493.

[14] Santa, A. C., Gómez, M. A., Castaño, J. G., Tamayo, J. A., and L. M. Baena. (2023). Atmospheric deterioration of ceramic building materials and future trends in the field: A review. *Heliyon*, vol. 9 (no. 4): e15028. doi: 10.1016/j.heliyon.2023.e15028.

[15] Luan, H., Wu, J., and J. Pan. (2021). Freeze-thaw durability of recycled aggregate concrete: An overview. *J. Wuhan Univ. Technol. Mater. Sci. Ed.*, vol. 36 (no. 1): pp. 58-69. doi: 10.1007/s11595-021-2378-x.
[16] Berrocal, C. G., Fernandez, I., and R. Rempling. (2022). The interplay between corrosion and cracks in reinforced concrete beams with non-uniform reinforcement corrosion. *Mater. Struct.*, vol. 55 (no. 4): 120. doi: 10.1617/s11527-022-01956-2.
[17] Wang, J., Ji, S., Huang, S., Jiang, Z., Wang, S., Zhang, H., Wang, Z., and J. Zhang. (2024). Crack sealing in concrete with biogrout: Sustainable approach to enhancing mechanical strength and water resistance. *Materials (Basel)*, vol. 17 (no. 7): 1568. doi: 10.3390/ma17071568.
[18] Alshammari, T. O., Pilakoutas, K., and M. Guadagnini. (2023). Effect of curing methods on plastic shrinkage cracking. *Constr. Mater.*, vol. 3 (no. 3): pp. 244-258.
[19] Pan, R., Yang, P., Shi, X., and T. Zhang. (2023). Effects of freeze-thaw cycles on the shear stress induced on the cemented sand-structure interface. *Constr. Build. Mater.*, vol. 371: 130671. doi: 10.1016/j.conbuildmat.2023.130671.
[20] Shen, Y., Wang, Y., Wei, X., Jia, H., and R. Yan. (2020). Investigation on meso-debonding process of the sandstone-concrete interface induced by freeze–thaw cycles using NMR technology. *Constr. Build. Mater.*, vol. 252: 118962. doi: 10.1016/j.conbuildmat.2020.118962.
[21] Wang, B., Liu, J., Wang, Q., Ling, X., Pan, J., Fang, R., and Z. Bai. (2024). Influence of freeze-thaw cycles on the shear performance of silty clay-concrete interface. *Cold Reg. Sci. Technol.*, vol. 219: 104120. doi: 10.1016/j.coldregions.2024.104120.
[22] Vagtholm, R., Matteo, A., Vand, B., and L. Tupenaite. (2023). Evolution and current state of building materials, construction methods, and building regulations in the U.K.: Implications for sustainable building practices. *Buildings*, vol. 13 (no. 6): 1546. doi: 10.3390/buildings13061546.
[23] Don, W., Suryanto, B., Tambusay, A., and P. Suprobo. (2022). Forensic assessments of the influence of reinforcement detailing in reinforced concrete half-joints: A nonlinear finite element study. *Structures*, vol. 38: pp. 689-703. doi: 10.1016/j.istruc.2022.02.029.
[24] Mohammad, S. N. A., Ming, W. K., Sam, G. T. Y., and X. Yeap. (2021). Effectiveness of sago waste as partial cement replacement in Sibu peat stabilisation. *Borneo J. Sci. Technol.*, vol. 3 (no. 1): pp. 93-98. doi: 10.35370/bjost.2021.3.1-12.
[25] Liu, C., Xu, X., Lv, Z., and L. Xing. (2020). Self-healing of concrete cracks by immobilizing microorganisms in recycled aggregate. *J. Adv. Concr. Technol.*, vol. 18 (no. 2): pp. 168-178. doi: 10.3151/jact.18.168.
[26] Lau, J. W., Ling, J. H., and Y. T. Lim. (2020). Feasibility study of reinforced concrete beam with embedded polystyrene spheres under incremental flexural load. *Borneo J. Sci. Technol.*, vol. 2 (no. 1): pp. 19-26.
[27] Albadrani, M. A., and A. D. Almutairi. (2024). Impact of eco-friendly plaster using epoxy resin and epoxy hardener on mechanical properties under compression and tension. *Polymers (Basel)*, vol. 16 (no. 9): 1205. doi: 10.3390/polym16091205.
[28] Sun, L., Hao, X., He, J., Cai, Y., Guo, P., and Q. Ma. (2024). Preparation and performance study of rapid repair epoxy concrete for bridge deck pavement. *Materials (Basel)*, vol. 17 (no. 7): 1618. doi: 10.3390/ma17071618.
[29] Uemura, K., Kadotani, K., Ichikawa, D., Goto, G., Takahara, R., and Y. Takahashi. (2025). Seismic performance of reinforced concrete column with repeated damage and repairs by resin injection. *Eng. Struct.*, vol. 325: 119463. doi: 10.1016/j.engstruct.2024.119463.
[30] Kim, T.-K., and J.-S. Park. (2021). Performance evaluation of concrete structures using crack repair methods. *Sustainability*, vol. 13 (no. 21): 12217. doi: 10.3390/su132112217.
[31] Lee, S., Lee, S., Kim, G., Son, M., Choe, G., Lee, J., and J. Nam. (2020). Effect of injecting epoxy resin adhesive into cement mortar on tile adhesion performance. *Appl. Sci.*, vol. 10 (no. 22): 8182. doi: 10.3390/app10228182.
[32] Guo, S.-Y., Zhang, X., Chen, J.-Z., Mou, B., Shang, H.-S., Wang, P., Zhang, L., and J. Ren. (2020). Mechanical and interface bonding properties of epoxy resin reinforced portland cement repairing mortar. *Constr. Build. Mater.*, vol. 264: 120715. doi: 10.1016/j.conbuildmat.2020.120715.

[33] Agbo, P., Mali, A., Deng, D., and L. Zhang. (2023). Bio-oil-based epoxy resins from thermochemical processing of sustainable resources: A short review. *J. Compos. Sci.*, vol. 7 (no. 3): 124. doi: 10.3390/jcs7030124.

[34] Wang, Y., Wang, C., and S. Zhou. (2022). Experimental study on repairing corroded cracks by electrophoretic deposition. *Appl. Sci.*, vol. 12 (no. 18): 9382. doi: 10.3390/app12189382.

[35] Liu, L., and B. Dong. (2021). Investigation of concrete crack repair by electrochemical deposition. *Int. J. Electrochem. Sci.*, vol. 16: 211217. doi: 10.20964/2021.12.19.

[36] Fang, Y., Du, K., Guo, Q., Feng, Q., Li, D., and C. Wang. (2021). Investigation of electrochemical chloride removal from concrete using direct and pulse current. *Constr. Build. Mater.*, vol. 270: 121434. doi: 10.1016/j.conbuildmat.2020.121434.

[37] Chen, Q., Xie, L., Zhu, H., Liu, W., Jiang, Z., Zhang, Z., Zhang, D., Li, B., and J. W. Woody Ju. (2024). Insight into ettringite induced concrete crack healing by electrodeposition: Effects of electrochemical parameters and numerical simulations. *Cem. Concr. Compos.*, vol. 149: 105504. doi: 10.1016/j.cemconcomp.2024.105504.

[38] Meng, Z., Liu, Q., She, W., Cai, Y., Yang, J., and M. Farjad Iqbal. (2021). Electrochemical deposition method for load-induced crack repair of reinforced concrete structures: A numerical study. *Eng. Struct.*, vol. 246: 112903. doi: 10.1016/j.engstruct.2021.112903.

[39] Sun, Y., Chen, Q., Zhu, T., Huang, A., and L. Xie. (2025). Electrochemical deposition method to repair leakage cracks in underground structures: Principle, laboratory experiment and field implementation. *Undergr. Sp.*, vol. 22 (no. 1): pp. 303-319.

[40] Lu, C., Ge, H., Li, Z., and Y. Zheng. (2022). Effect evaluation of microbial mineralization for repairing load-induced crack in concrete with a cyclic injection-immersion process. *Case Stud. Constr. Mater.*, vol. 17: e01702. doi: 10.1016/j.cscm.2022.e01702.

[41] Jadhav, U. U., Lahoti, M., Chen, Z., Qiu, J., Cao, B., and E.-H. Yang. (2018). Viability of bacterial spores and crack healing in bacteria-containing geopolymer. *Constr. Build. Mater.*, vol. 169: pp. 716-723. doi: 10.1016/j.conbuildmat.2018.03.039.

[42] Omoregie, A. I., Muda, K., Ong, D. E. L., Ojuri, O. O., Bin Bakri, M. K., Rahman, M. R., Basri, H. F., and Y. E. Ling. (2023). Soil bio-cementation treatment strategies: State-of-the-art review. *Geotech. Res.*, vol. 11 (no. 1): pp. 3-27. doi: 10.1680/jgere.22.00051.

[43] Janek, M., Fronczyk, J., Pyzik, A., Szeląg, M., Panek, R., and W. Franus. (2022). Diatomite and Na-X zeolite as carriers for bacteria in self-healing cementitious mortars. *Constr. Build. Mater.*, vol. 343: 128103. doi: 10.1016/j.conbuildmat.2022.128103.

[44] Soysal, A., Milla, J., King, G. M., Hassan, M., and T. Rupnow. (2020). Evaluating the self-healing efficiency of hydrogel-encapsulated bacteria in concrete. *Transp. Res. Rec.*, vol. 2674 (no. 2): pp. 113–123.

[45] Khan, M. B. E., Shen, L., and D. Dias-da-Costa. (2021). Self-healing behaviour of bio-concrete in submerged and tidal marine environments. *Constr. Build. Mater.*, vol. 277: 122332. doi: 10.1016/j.conbuildmat.2021.122332.

[46] Zhang, L. V., Nehdi, M. L., Suleiman, A. R., Allaf, M. M., Gan, M., Marani, A., and M. Tuyan. (2021). Crack self-healing in bio-green concrete. *Compos. Part B Eng.*, vol. 227: 109397. doi: 10.1016/j.compositesb.2021.109397.

[47] Raza, A., and R. A. Khushnood. (2022). Repair of mortar cracks using *bacillus pumilus* based bio-suspension assessed by machine learning algorithm for image processing. *J. Build. Eng.*, vol. 61: 105267. doi: 10.1016/j.jobe.2022.105267.

[48] Ran, M., Zhou, X., Yan, Y., Jiang, R., and X. Zhou. (2023). Grouting mechanism of polyurethane composite materials in asphalt pavement subsidence. *Materials (Basel)*, vol. 16 (no. 11): 4015. doi: 10.3390/ma16114015.

[49] Waqar, A., Shafiq, N., Bheel, N., Benjeddou, O., Hamah Sor, N., Hu, J. W., Najm, H. M., and H. R. Almujibah. (2024). Modeling of success factors of using PU coats in concrete construction projects. *Heliyon*, vol. 10 (no. 3): e28908. doi: 10.1016/j.heliyon.2024.e28908.

[50] Haruna, S. I., Ibrahim, Y. E., and A. Al-shawafi. (2024). Evaluation of bond strength of concrete repaired using polyurethane grout material under static and impact loads coupled with statistical analysis. *Polymers (Basel)*, vol. 16 (no. 19): 2729. doi: 10.3390/polym16192729.

[51] Zhang, L., Huang, C., Li, Z., Wang, A., Gao, M., Gao, Y., and X. Wang. (2024). Experimental study on water-plugging performance of grouted concrete crack. *Materials (Basel)*, vol. 17 (no. 7): 1568. doi: 10.3390/ma17071568.

[52] Park, J.-G., Seo, D.-J., and G.-H. Heo. (2022). Impact resistance and flexural performance properties of hybrid fiber-reinforced cement mortar containing steel and carbon fibers. *Appl. Sci.*, vol. 12 (no. 22): 11397. doi: 10.3390/app122211397.

[53] Lei, X., Lin, S., Meng, Q., Liao, X., and J. Xu. (2020). Influence of different fiber types on properties of biocemented calcareous sand. *Arab. J. Geosci.*, vol. 13 (no. 11): 400. doi: 10.1007/s12517-020-05309-7.

[54] Ren, D., Fan, S., He, L., Liu, Y., Deng, S., Luo, Y., Wang, P., Jin, X., and J. Li. (2025). Covalent deposition of Diels-Alder reaction on polyester fiber surface and its enhancement mechanism on SBS-modified asphalt. *J. Appl. Polym. Sci.*, vol. 142 (no. 5): e56712. doi: 10.1002/app.56712.

[55] Bisht, V., Chaurasia, L., and L. P. Singh. (2020). Studies on corrosion and carbonation resistance by bacteria-mediated mineralization in concrete. *ACI Mater. J.*, vol. 117 (no. 2): pp. 13-26. doi: 10.14359/51724610.

[56] Xie, D., Zhang, R., and J. Wang. (2023). The influence of environmental factors and precipitation precursors on enzyme-induced carbonate precipitation (EICP) process and its application on modification of recycled concrete aggregates. *J. Clean. Prod.*, vol. 395: 136444. doi: 10.1016/j.jclepro.2023.136444.

[57] Jiang, Y., Hu, X., and Y. Liu. (2021). Long-term performance of glulam-lightweight concrete composite beams with screw connections. *Constr. Build. Mater.*, vol. 310: 125227. doi: 10.1016/j.conbuildmat.2021.125227.

[58] Regalla, S. S., and N. Senthil Kumar. (2025). The enhancing role of nanomaterials in revolutionizing ultra-high-performance concrete (UHPC): A journey from atomic precision to structural prominence. *Case Stud. Constr. Mater.*, vol. 22: e04608. doi: 10.1016/j.cscm.2025.e04608.

[59] Wang, W., Yang, H., and C. Xiang. (2023). Green roofs and facades with integrated photovoltaic system for zero energy eco-friendly building - a review. *Sustain. Energy Technol. Assessments*, vol. 60: 103426. doi: 10.1016/j.seta.2023.103426.

[60] Dinkel, E., Braun, B., Schröder, J., Muhrbeck, M., Reul, W., Meeder, A., Szewzyk, U., and T. Scheytt. (2020). Groundwater circulation wells for geothermal use and their impact on groundwater quality. *Geothermics*, vol. 86: 101812. doi: 10.1016/j.geothermics.2020.101812.

[61] Wang, X.-Y. (2018). Effects of crack and climate change on service life of concrete subjected to carbonation. *Appl. Sci.*, vol. 8 (no. 11): 2085. doi: 10.3390/app8112085.

[62] Kumar Sahu, P. (2022). Defects in concrete in building construction. *J. Adv. Geotech. Eng.*, vol. 5 (no. 1): pp. 1-16.

[63] Wang, Q., Huang, B., and Y. Gao. (2025). Current status and prospects of digital twin approaches in structural health monitoring. *Buildings*, vol. 15 (no. 1): 40. doi: 10.3390/buildings15010040.

[64] Li, W., Zhu, J., Mu, K., Yang, W., Zhang, X., and X. Zhao. (2024). Experimental investigation of concrete crack depth detection using a novel piezoelectric transducer and improved AIC algorithm. *Buildings*, vol. 14 (no. 2): 480. doi: 10.3390/buildings14020480.

[65] Rashad, A. M., and M. Gharieb. (2021). Solving the perpetual problem of imperative use heat curing for fly ash geopolymer cement by using sugar beet waste. *Constr. Build. Mater.*, vol. 307: 124902. doi: 10.1016/j.conbuildmat.2021.124902.

[66] Machorro-Lopez, J. M., Hernandez-Figueroa, J. A., Carrion-Viramontes, F. J., Amezquita-Sanchez, J. P., Valtierra-Rodriguez, M., Crespo-Sanchez, S. E., Yanez-Borjas, J. J., Quintana-Rodriguez, J. A., and L. A. Martinez-Trujano. (2023). Analysis of acoustic emission signals processed with wavelet transform for structural damage detection in concrete beams. *Mathematics*, vol. 11 (no. 14): 3064. doi: 10.3390/math11143064.

[67] Ciampa, F., Mahmoodi, P., Pinto, F., and M. Meo. (2018). Recent advances in active infrared thermography for non-destructive testing of aerospace components. *Sensors*, vol. 18 (no. 5): 1609. doi: 10.3390/s18051609.
[68] Górszczyk, J., Malicki, K., and T. Zych. (2019). Application of digital image correlation (DIC) method for road material testing. *Materials (Basel)*, vol. 12 (no. 18): 2914. doi: 10.3390/ma12182914.
[69] Olaszek, P., Maciejewski, E., Rakoczy, A., Cabral, R., Santos, R., and D. Ribeiro. (2024). Remote inspection of bridges with the integration of scanning total station and unmanned aerial vehicle data. *Remote Sens.*, vol. 16 (no. 9): 1528. doi: 10.3390/rs16091528.
[70] Tserpes, K., and V. Tzatzadakis. (2022). Life-cycle analysis and evaluation of mechanical properties of a bio-based structural adhesive. *Aerospace*, vol. 9 (no. 11): 698. doi: 10.3390/aerospace9110698.