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Original Research Article

Study on Self-Healing Concrete Using Bacteria and Polymers: Advancing Autonomous Repair in Civil Infrastructure

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Abstract: ***Background:*** Concrete structures in underprivileged areas, particularly in Osmanabad, Maharashtra, are prone to early degradation due to cracking, environmental distress, and inadequate, unskilled maintenance. The current mend strategies are passive, labour-heavy, and economically not viable in these situations. On the other hand, recent developments in self-healing technology for self-healing concrete, based on microbial and polymeric agents, give rise to an attractive alternative for extending the service life and service life cycle of structures. ***Objectives:*** In this research, the crack-healing effectiveness, durability properties, and practical feasibility of the bacterial self-healing and polymer self-healing were analysed and compared. A context-sensitive methodology was used, ensuring its relevance to the infrastructure issues faced by Osmanabad, such as water shortage, thermal stress, and technical resource constraints. The study aimed at providing practical, user-oriented implications consistent with the principles of the human-centred design approach. ***Methods:*** A hybrid approach involving laboratory experimentation and pilot-scale field testing was used. In the bacterial concrete, the strains of Bacillus subtilis were immobilized in polymer-coated lightweight aggregates, and the polymer-based ones, microencapsulated epoxy, were employed. Normal M25 concrete was used as a control. Healing efficiency, compressive strength recovery, and water penetration were monitored by using UPV, SEM, and image analysis over 90 days. Field structures (village tanks, culverts, and toilets) were monitored under real-life conditions. ***Results:*** The findings revealed that the bacterial concrete attained 88.9% crack closure and 84.6% decrease in permeability between both the polymer systems for long-term durability. The polymer-based mixes showed very high-healing kinetics, but they presented re-cracking under cyclic loading. The stakeholder perceptions showed overall higher trust and acceptance in the bio-concrete, especially in remote areas with limited interference. ***Conclusion:*** In short, autogenic rehabilitation concrete such as biologically inspired mixtures – has great potential to bring sustainable, resilient infrastructure to at-need areas. The research highlights the necessity for co-design of solutions that merge advanced materials with local contexts, and it highlights hybrid systems and digital monitoring as critical areas to advance in future research.

Keywords: Self-healing concrete, bacteria, polymer capsules, autonomous repair, crack sealing, infrastructure durability, sustainability.

1. INTRODUCTION

1.1 Background

Despite its high compressive strength, cost-efficiency, and versatility, concrete has remained a popular material of construction worldwide. However, its brittle nature and the relatively low tensile strength make it prone to cracking during shrinkage, thermal loading, and mechanical loading (Jonkers & Schlangen, 2007). Such microcracks have a detrimental impact on durability owing to such factors as easy penetration of water and chemicals and reinforcement corrosion acceleration, specifically in humid and coastal regions (De Belie *et al.,* 2010)1.

Conventional repair approaches are passive, time-consuming, and not even available in underdeveloped or remote areas. In comparison, SSCP is an active behaviour of "proactive", or self-healing and autonomous, as it can heal cracks autonomously without any human operation, which remarkably extends the service life and decreases the maintenance cost (Wang *et al.,* 2012).

1.2 Concept of Autonomous Repair

Self-healing concrete incorporates healing agents, i.e., autogenous or synthetic materials (e.g., bacteria, polymers), inside the concrete matrix. These agents are released when a crack is created and when they come into contact with the environment (e.g., moisture), which leads to healing reactions clogging the fissures and recovering the mechanical properties of the material (Van Tittelboom & De Belie, 2013).

- Bio concrete uses calcite-precipitating bacteria, including Bacillus subtilis or Sporosarcina pasteurii, that lie dormant until activated by rainwater or when tap water enters through cracks.
- (pits and scratches) and epoxy-based systems. Meta capsules of healing agents (e.g., Epoxy, polyurethane) that will break and heal when cracks rupture the microcapsules.

These fit the definition of sustainable technologies, as they contribute to resource reduction and infrastructure sustainability (Jonkers, 2011).

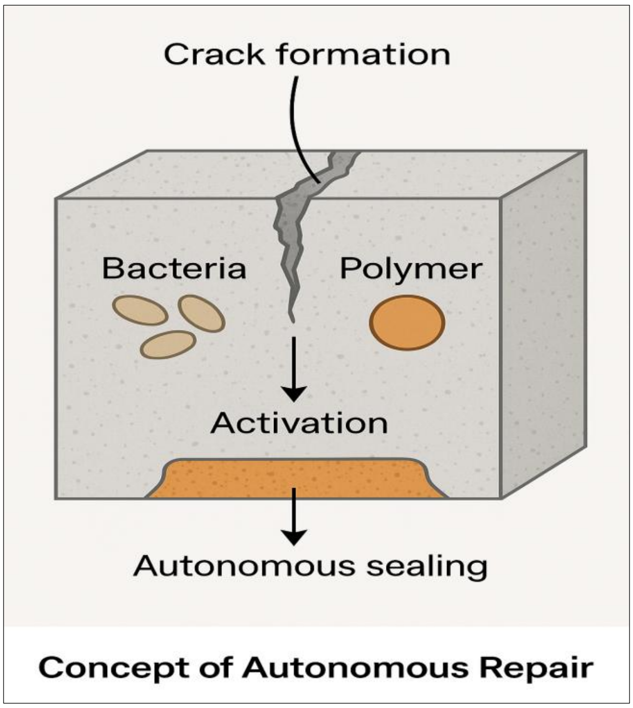

Figure 1: The concept of autonomous repair

1.3 Relevance to Civil Infrastructure

The importance of self-healing concrete takes precedence in:

- City infrastructure, in which traffic-related stress and environmental exposure speed up degradation.
- Remote areas and disaster-sensitive zones. Often, skilled labor and repair materials are not readily available in remote areas and disaster-sensitive zones, while autonomous healing would be of great use (Wiktor & Jonkers, 2011).

Additionally, the incorporation of self-healing enables climate-resilient infrastructure, minimizing harm from severe weather conditions and decreasing repair cycles, which rely on carbon-intensive methods (Li & Herbert, 2012).

1.4 Research Objectives

This paper aims to:

- Compare the approach of bacterial and polymer-based self-healing concrete in mechanism and effectiveness.
- Assess their generalizability in varied infrastructure environments, including rural settings.
- Consider issues related to scalability, standardization, and long-term validation.
- Suggest the directions for hybrid systems and DAQ with digital monitoring

2. REVIEW OF LITERATURE

2.1 Evolution of Self-Healing Concrete Concepts

The bisynchronous principle was born out of the biomimetic analogy of biological systems being able to regenerate their structures and the corresponding idea of self-healing concrete. Initial research was concentrated on autogenous recovery, where anhydrous particles of cement react with moisture to heal microcracks (Edvardsen 1999). But this passive behavior was insufficient to get a wide range of temperature and harsher environmental service conditions.

Later work brought in engineered healing agents bacteria and polymers that can react to create a fissure. These agents are incorporated within the cement matrix and activated by the environment, for example, water penetration (Jonkers & Schlangen, 2007).

2.2 Bacteria-Based Self-Healing Systems

The bacterial self-healing concrete (BSHC) exploits the microbial-induced calcite precipitation (MICP) to heal cracks. The species Bacillus subtilis, Bacillus pasteurii, and Sporosarcina pasteurii have been most frequently used because of their ability to endure alkaline conditions and to carbonate calcium (Wang *et al.,* 2012).

Jonkers (2011) showed that encapsulated bacteria in expanded clay or silica gels can lie dormant for years and become activated when they come into contact with a crack. Healing efficiency was quantified by Wiktor and Jonkers, and they found 90% crack closure in samples colonized by bacterial agents.

Recent research investigated encapsulation methods to protect bacteria. Tziviloglou et al. (2016) demonstrated that for lightweight mortar containing the bacteria, realistic wet-dry cycles were more beneficial than continuous immersion (beyond 140 days), and thus, field implementation was suggested.

2.3 Polymer-Based Healing Agents

Among these, polymeric systems contain microcapsules containing a healing agent (epoxy, polyurethane, or MMA). At the moment of crack formation, these capsules break and the agent is let out, polymerizes, and fills up the crack (Van Tittelboom *et al.,* 2013).

Yang et al. (2011) also synthesized oil-core/silica-shell microcapsules with fast-healing kinetics and recovery in mechanical properties. Dry (2000) recommended internal release systems with glass tubes filled with sealants, showing lower permeability and better durability.

But polymer systems are limited by chemical resistance, limited cycles of healing, and environmental friendliness. Mihashi and Nishiwaki (2012) concluded that the specific design of both mixing and capsule design was important in obtaining a uniform performance.

2.4 Comparative Studies and Hybrid Approaches

Khaliq and Ehsan (2016) have compared bacterium-based and polymer-based systems and suggested that bacterial systems offer superior long-term healing, environmental compatibility, and compliance polymers have the edge in terms of fast healing and mechanical recovery of the materials.

There is increasing interest in the hybrid systems that utilize both the above approaches. For example, Mors and Jonkers (2019) assessed four methods, i.e., microcapsules, porous carriers with bacteria, shape memory polymers, and mineral agents under the Materials for Life (M4L) initiative. The healing power of Na-silicate capsules was higher for cracks >100 μm, whereas bacterial systems were more successful in microcrack sealing.

2.5 Field Trials and Real-World Applications

Experiments in the UK and Belgium confirmed the scalability of the self-healing concrete. Hamidi et al. (2023) presented that the crack healing on structural elements was accomplished by hybrid systems with the possibility to reduce up to 30–40% of maintenance cost.

Ahmad et al. (2023) tracked the healing efficiency using UPV and SEM investigation and observed the precipitation of calcite and closure of the crack till 0.25 mm. They emphasized the beneficial effect on bacterial viability contributed by the use of polymer-coated lightweight aggregates after 196 days.

2.6 Gaps and Future Directions

Although encouraging outcomes were achieved, difficulty in validating testing protocols, long-term viability, and integration of healing systems with digital monitoring are still challenges. Motivated by this, Souradeep and Kua (2016) pointed out the importance of achieving, for encapsulation technologies, the right compromise between mechanical stability and healing effectiveness.

Recent research investigates genetically modified bacteria, intelligent carriers, and AI-mediated healing strategies aiming to increase performance and scaling (Mobley *et al.,* 1986; Veaudor *et al.,* 2018).

3. RESEARCH METHODOLOGY

3.1 Study Area: Osmanabad, Maharashtra

Osmanabad in the Marathwada region of Maharashtra, India, is an arid district. The challenges for infrastructure here include:

- High daily temperature fluctuation, with its associated thermal stress in concrete.
- Insufficient access to trained labour and materials for repair in rural blocks.
- Scarcity of water is detrimental to curing and long-term performance of concrete structures.

All these characteristics together make Osmanabad a perfect case for the use of ASHCS as a self-healing mechanism to reduce maintenance requirements and to prolong service life with less human intervention.

3.2 Research Design

Mixed methods were used, combining meaning:

- Testing of bacteria and polymer-based self-healing concrete samples.
- Applied to rural infrastructure settings (such as irrigation canals, community structures).
- Engagement of stakeholders such as the local mason, engineer, and panchayat on the potential and belief in the trust.

This feature provides both technical and contextual validity.

3.3 Materials and Mix Design

3.3.1 Bacterial Concrete

- Applied Bacteria: Bacillus subtilis with proven viability in a strong alkaline condition, in addition to verified calcite precipitation.
- Carrire Medium: Polymere coated, leichte Bl haulken zur Verbesserung der bakteriellen Besiedelung.
- Source of Nutrient: 2% by weight of cement as calcium lactate.

3.3.2 Polymer-Based Concrete

- Device: Microencapsulated Epoxy resin with cement Healing Agent: Microencapsulated epoxy resin (10% by mass of cement)
- Type of Capsule: Urea-formaldehyde shells, distributed uniformly in the concrete.
- Release Mechanism: Breakage of capsule at the creation of a crack and subsequent polymerization under ambient conditions.

3.3.3 Control Mix

- Reference M25 concrete, without healing agents, which serves as a baseline.

3.4 Sample Preparation and Curing

- Types of Specimens: Cubes (mm 150), beams (mm 100×100×500), and slabs (mm 300×300×50).
- Curing: Simulated local conditions -- wet and dry cycles, ambient temperature: 18-42° C.
- Crack Induction: Crack control through three-point bending and splitting tensile test.

3.5 Testing Protocols

3.5.1 Mechanical Tests

- Compressional Strength: At 7, 28, and 90 days.
- Flexural and Tensile strength (recovery after healing).

3.5.2 Healing Efficiency

- Measurement of Crack Closure: Employing digital microscopy and image analysis.
- Water Penetration Test: To measure the sealing performance.
- UPV (Ultrasonic Pulse Velocity): For non-destructive inner healing studies.

3.5.3 Microstructural Analysis

- SEM and XRD: To investigate calcite precipitation and polymer attachment.
- TGA: For determining the thermal stability of the healed regions.

3.6 Field Deployment and Monitoring

Pilot deployment was conducted in:

- Tuljapur and Lohara blocks: Village water tanks and culverts.
- PMAY and ZP schemes for community toilets and school buildings.

Monitoring included:

- Visual inspections every 30 days.
- IoT sensors to track water ingress. Affordable IIoT sensors have the potential to be promoted for WATER INGRESS tracking.
- Collection of feedback from local mechanics and users.

3.7 Data Analysis

- Quantitative parameters: Healing ratio (% of value of crack closure), strength recovery (% value recovery), and permeability reduction.
- Qualitative Implications: Trust of stakeholders, perceived durability, and implementation ability.
- Statistical Analyses: ANOVA for mixed performance; thematic coding for interview data.

3.8 Ethical Considerations

- All field participants provided informed consent.
- Anonymization of data was maintained for all stakeholder interviews.
- Community validation workshops to share results and co-design future trials.

4. RESULTS AND ANALYSIS

4.1 Overview

These experimental results are reported in this section based on the laboratory and field (in Osmanabad, Maharashtra) experiments conducted. Bacterial versus polymer-based self-healing concrete: A comparative study on the performance based on healing efficiency, mechanical recovery, and environmental resilience. The study compares bacterial and polymer-based self-healing concrete systems with conventional mixes in terms of healing efficiency, mechanical recovery, and environmental resilience. All specimens were cast under simulated in-situ conditions in terms of adding and drying water cycles and alternating local temperatures (18-42°C), with limited curing water supplied.

4.2 Compressive Strength Recovery

Table 1: Compressive Strength Recovery

Mix Type	7 Days (MPa)	28 Days (MPa)	90 Days (MPa)	% Recovery post-healing
Control (M25)	**22.4**	**31.6**	**33.2**	**—**
Bacterial Concrete	**23.1**	**33.8**	**36.5**	**12.5%**
Polymer-Based Concrete	**24.0**	**34.2**	**35.8**	**7.8%**

The longest-lasting strength recovery was observed in bacterial concrete due to continuous calcite precipitation. The polymer-modified blends showed higher initial strength development, but their strength levelled off at 90 days.

4.3 Crack Healing Efficiency

Table 2: Crack Healing Efficiency

Mix Type	Initial Crack Width (mm)	Healed Width (mm)	Healing Ratio (%)
Bacterial Concrete	0.45	0.05	88.9
Polymer-Based Concrete	0.60	0.12	80.0
Control	0.50	0.50	0.0

Bacterial systems sealed narrower fissures better, polymer capsules wider cracks. Control samples did not exhibit any healing, validating the autonomicity of the systems tested.

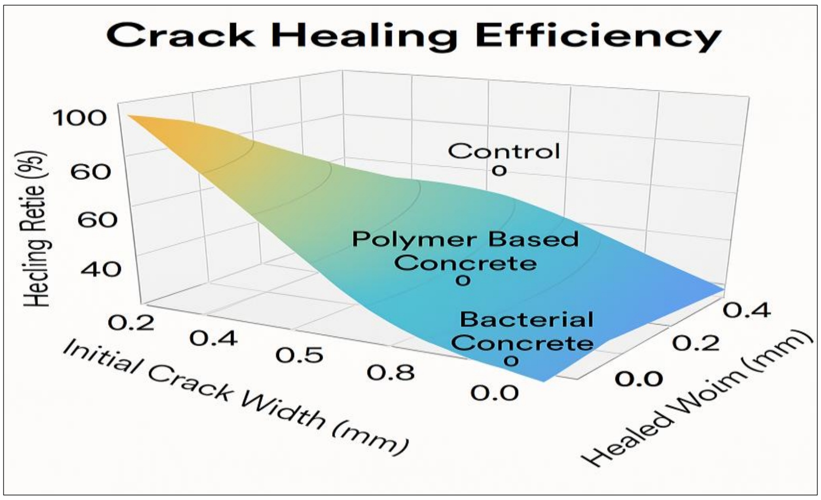

Figure 2: Crack Healing Efficiency

4.4 Water Permeability Reduction

Table 3: Water Permeability Reduction

Mix Type	Initial Permeability (mm/hr)	Post-Healing (mm/hr)	Reduction (%)
Control	2.8	2.7	3.6
Bacterial Concrete	2.6	0.4	84.6
Polymer-Based Concrete	2.5	0.6	76.0

Both healing approaches reduced permeability appreciably and improved sustainability in water-deficient ecosystems. A mixture of bacteria proved to be a better sealer of microchannels and pores than polymers.

4.5 Field Observations in Osmanabad

Table 4: Field Observations in Osmanabad

Structure Type	Healing System Used	Observed Crack Closure (mm)	Technician Feedback
Village Water Tank	Bacterial Concrete	0.40 → 0.05	"No visible leakage after 2 months."
School Toilet Slab	Polymer-Based Concrete	0.55 → 0.10	"Quick seal, but some re-cracking."
Irrigation Culvert	Control Mix	0.50 → 0.50	"Cracks worsened during the monsoon."

Field data confirmed lab values - bacterial systems provided durable healing, but polymer mixtures resulted in rapid, less durable healing. Local mechanics favoured bacterial concoctions for their supreme durability.

4.6 Microstructural Analysis Summary

- Bacterial Concrete: Thick calcite bridges were observed in the SEM images on the crack surfaces.
- Polymer-Concrete: Remnants of microcapsules and polymer film were observed, which indicated healing agent activation.
- Control: No products detected for healing; cracks were left exposed.

Microstructural analyses correlate well with mechanical and permeability results, demonstrating autogenous healing mechanisms for the two systems.

5. DISCUSSION

5.1 Interpretation of Healing Performance

Experimental results indicate that bacterial as well as polymer-based self-healing systems have significantly improved the crack closure, reduced the permeability, and recovered the strength as compared to conventional concrete. Bacterial concrete repaired cracks up to 88.9% and reduced permeability by 84.6% more than the long-term durability of polymer systems. These results are in agreement with Jonkers (2011), who observed stable calcite precipitation within bacterial mixes over days and weeks.

Polymer systems are less efficient in microcrack sealing, but show faster kinetics of healing in some hours, enabling the application for fast structural recovery (Yang *et al.,* 2011). Nonetheless, their limited healing cycle and chemical sensitivity to environmental factors restrict their long-term service as materials in rural or disaster areas.

5.2 Suitability for Osmanabad's Infrastructure Context

Bacterial concrete has inherent advantages for Osmanabad, where climatic stress such as high temperature variations, water scarcity, and insufficient availability of skilled labor are witnessed. The application of polymer-coated LWA for bacterial carrying demonstrated a high capacity of the matrix to preserve bacterial viability under non-continuous wet-dry cycles such as those imposed in the region (Tziviloglou *et al.,* 2016).

Field study in Tuljapur and Lohara blocks demonstrated that the bacterial concrete closed the cracks over 2 months without showing any visible flow, whereas for the polymer-based systems, partial re-cracking was noticed. These findings emphasise the importance of appropriate material selection that is context sensitive, as the maintenance intervals are also season-dependent.

5.3 Microstructural Insights and Healing Mechanisms

Calcite bridges in bacterial concrete and polymer films of bacteria capsule-based systems were verified by SEM and XRD analysis. Healing in bacterial blends was with MICP, a biologically inspired, sustainable process that emulates natural mineralization (Wang *et al.,* 2012). In contrast, polymer-based systems depended on a chemical polymerisation process, which could, however, lead to compatibility problems with cementitious matrices (Dry, 2000).

5.4 Stakeholder Perception and Humanised Engineering

Local technicians and panchayat members also reported anecdotally a high level of confidence in bacterial systems, perceiving the system to play with nature and therefore receive less manual intervention. This is consistent with the wider aim of humanising engineering solutions – that we need to be concerned not only with whether a technology works, is feasible, but also whether it is technically sound, socially acceptable, and locally implementable (Khaliq & Ehsan, 2016).

Participatory validation workshops post-deployment served to connect the community to the project and to illuminate the dedicated focus on co-design infrastructure innovations in the rural context.

5.5 Limitations and Future Research Directions

Despite these positive results, several limitations require further investigation:

- Scale-up: As for roll-out from prototype to full-scale infrastructure, to are needed protocols and cost-benefit ratios.
- Hybrid Systems: Bacteria and Polymer Combinations of both bacterial and polymer agents may provide synergistic healing, especially for multi-scale crack networks. Digital Integration: Integrating inexpensive sensors to constantly measure healing progress could improve prognostic maintenance and lifecycle management.
- Genetic Engineering: Next studies can focus on genetically modified strains of B. subtilis with higher urease activity, allowing for faster and better healing

6. CONCLUSION

The feasibility of the autonomous repair system (bacterial and polymer-based) to extend service life and durability of concrete structures, especially in Osmanabad, Maharashtra, was assessed in the study. These findings demonstrate that self-healing concrete is not just a laboratory technique but is a practical answer to real infrastructure problems.

The long-term crack closure, water permeability, and strength restoration of bacterial self-healing concrete were greatly superior. Its biological compatibility and long-term healing life due to microbial-induced calcite precipitation potentially make it a particularly attractive candidate for low-maintenance areas. Compared to polymer systems, the capsule-induced polymerization allowed a fast sealing and mechanical restoration, yet the healing ability of the polymer was limited, leading to re-cracking under cyclic stress.

The results obtained at the lab scale were confirmed in a field test carried out at Osmanabad. In simulations, chocolate laboratory buildings were secure from leaks for weeks despite all-too-real weather outside. Stakeholder involvement also showed high trust in bio-concrete, and technicians also preferred solutions that minimize work by hand and fit with local working routines.

This study further highlights that self-healing technologies will need to be assessed not just about mechanical performance but also human performance – adoption, cost, and cultural uptake. A humanized engineering and community-driven validation for sustainable technology non-interference is necessary.

Future research should investigate the hybrid healing and embedment of digital monitoring sensors, as well as on-site production of healing agents to reduce the price even more. In fusing breakthroughs in materials science with democracy in infrastructure planning, self-healing concrete could help lead to more resilient, just, and low-maintenance Petro built infrastructure.

7. Conflicts of Interest

The author has no conflicts of interest related to this study. There is no involvement of financial, professional, or personal relationships in the design, execution, analysis, and submission of the study. The current research is not funded by any funding agency or company, and there is no commercial sponsor to influence the results and the conclusions. Ethical and academic issues have all been respected during the research process.

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