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Study on Use of Recycled Construction and Demolition Waste in Structural Applications: A Life-Cycle and Performance-Based Evaluation

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Abstract- Background: Rural areas such as Osmanabad are plagued by sustained degradation of infrastructure driven by climate variation, material fatigue, and restricted maintenance capabilities. Structural concrete, while strong, is susceptible to microcracking that can expedite deterioration and impede long-term resilience. Fostered by the recent advent of self-healing technologies, namely bio-concrete and polymer-fused conduit systems, these represent adequate solutions for low or no-maintenance, climate-responsive, and adaptable buildings in impoverished areas. Objectives: The current study is set forth with the objectives of field performance, healing potential, and stakeholders' acceptance for the bio-concrete and polymer-based self-healing concrete (SHC) under semi-arid conditions in Osmanabad. It aims at the transition from laboratory innovation to rural deployment conditions, highlighting humanised engineering and participatory validation. Methods: A mixed-method design of experimental trials in 3-gram panchayats was implemented with stakeholder involvement. Quantitative data were compressive strengths, crack closure rates, and environmental (humidity, temperature) correlation variables. Qualitative information was obtained through interviews, focus groups, and participatory observation. The analytic techniques used were ANOVA, regression modelling, and thematic coding of the data. Results: Bio-concrete exhibited enhanced crack healing (94% recovery) and strength increases (~20% compared to control mixes), especially in high-humidity zones. Positive correlations were found between healing rates and environmental humidity. The highest level of trust from the stakeholders was observed from the farmers (avg. rating: 9.1/10), noting that it helped minimize maintenance and seemed to heal. The polymer SHC had milder performances, though lower photo-hysteresis. Conclusion: Bio-concrete is found to be a socially and technically acceptable, climate change resilient alternative for rural infrastructure. The research confirms its relevance in Osmanabad and supports community-scale scaling. Through the convergence of high-performance materials and ethical, participatory adoption, this research configures a new model of resilient, humanised infrastructure for the disenfranchised.

Keywords- Self-healing concrete, bio-concrete, polymer-based systems, climate-resilient infrastructure, Osmanabad field trials, participatory engineering, crack closure efficiency.

I. INTRODUCTION

Background and Rationale

Construction is one of the highest users of natural resources and a significant contributor to the global waste stream, generating more than 2.36 billion tons of construction and demolition waste (CDW) annually (Alibeigibeni et al., 2025). It is estimated that in India alone, CDW generated annually is over 150 million tons, with a very small proportion being recycled or reused (Singh & Harvinder, 2021). The increasing use of unsustainable materials such as concrete, known for its large carbon footprint, has led to a paradigm shift to circular construction, in which waste is no longer considered a liability but a resource.

Recycled aggregates and bricks from CDW offer a more promising alternative for structural use, which usually demands the most materials. Their reutilisation conforms to the 4Rs principle (Reduce, Reuse, Recycle, Recover) and is consistent with the legal prescriptions in India, ranging from the C&D Waste Management Rules, 2016 (BMTPC, 2018).

Circular Construction Economy

Circular building subverts the linear "take-make-dispose" model to enhance design for disassembly, material rescue, and reuse of structural elements (Zeeshan, 2024). The approach focuses on modularity, long life, and resource economy, allowing the building to respond to varied uses over time and reduce waste and resource consumption.

Around the world, circular construction is gaining traction in policy frameworks such as the EU Circular Economy Action Plan and India's National Resource Efficiency Policy. The requirement in these frameworks for 70–100% recycling of CDW has implications for the use of recycled materials in mainstream infrastructure (ECESP 2025).

Structural Viability of Recycled Materials

It has been reported that crushed CDW particles exhibit superior mechanical performance against RAC and pressure-compacted recycled bricks for structural applications. Research indicates that RAC is already being produced from recycled bricks with a compressive strength of 25–35 MPa, representing the RAC cube not devoting < 10 MPa for IS:2185 and IS:456 standard using RAC to produce blocks (Alibeigibeni et al., 2025; Shelke & Deshmukha, 2018).

Nonetheless, these materials suffer from certain shortcomings related to porosity, water uptake, and interfacial adhesion.

These can be addressed by the use of admixtures, geopolymer binders, and optimized mix designs, which render recycled materials suitable for load-bearing applications (Amezquita Vaca et al., 2023).

Life-Cycle Assessment (LCA) and Sustainability

LCA allows you to take a full view of environmental impact throughout the material's life cycle— from resource extraction to landfill. RAC and recycled bricks have been able to achieve 25–45% of CO_2 emissions, energy savings, and water savings compared to conventional materials (Wang et al., 2023; Concrete Captain, 2025).

By integrating LCA into building codes and procurement policies, the industry is able to make sustainability something more than just a feel-good concept – it's something tangible. It is also in line with India's zero-waste preference of over 95% diversion of CDW from landfills (PW Only IAS, 2024).

Legal Mandates and Policy Drivers

The regulatory scene in India is being transformed to facilitate the reuse of CDW. The C&D Waste Management Rules (2016) make it mandatory for CDW to be segregated, processed, and reused in urban projects. Construction material is now part of Extended Producer Responsibility (EPR), and developers are being asked to factor in end-of-life recovery (Lawrbit, 2022). Decentralized recycling centers, mobile crushers, and Reverse logistics are being promoted by Urban bodies as well, to enable material reuse right on the site. Such policies are helpful in decreasing pressure on landfills and generating employment, and declining construction costs (India Law LLP, 2024).

II. REVIEW OF LITERATURE

Circular Construction Economy

The circle of building economy challenges the classical linear model, featuring eco-design for disassembly, materials Recovery, and reuse of structural elements (Gasparri et al., 2023). It intends to close material loops and cut the use of resources and waste generation from construction to the end of the life of a building. Material passports, demounting ability, and reverse logistics are key to this new paradigm (Cheung et al., 2023).

At the global level, the circularity in construction is influenced by the policy initiatives, for example, the EU Waste Framework Directive requiring 70% CDW recovery by weight (Swarnakar & Khalfan, 2024). In India, circular practices are legally framed in the National Resource Efficiency Policy and C&D Waste Management Rules (2016) (Sonavale et al., 2023).

Despite increasing attention, there are still knowledge gaps in the areas of economic sustainability, stakeholder participation, and digital integration (Zhang et al., 2025). New paradigms suggest circular networks, process innovation, and provenance of products to promote uptake (Gasparri et al., 2023).

Structural Performance of Recycled Materials

Recycled bricks and RAC have demonstrated potential capacity when processed and designed properly. High compression strength (25–35 MPa) sufficient for structural usage has been achieved for RAC according to studies (Alibeigibeni et al., 2025). Recycled bricks have a compressive strength of more than 10 MPa. Before compressing with pressure, compacting would meet IS:2185 (Joseph et al., 2023).

However, the issues are problems such as higher porosity, poorer ITZ (interfacial transition zone), and lower modulus of elasticity (McNeil & Kang, 2013). These are reducible with the use of admixtures, geopolymer binders, and through fiber addition (Goyal & Goyal, 2019). The results of the structural tests show that the RAC beams have larger midspan deflections while acceptable ultimate moments are saved (McNeil & Kang, 2013).

recycled aggregates, nano-silica treatments, and accelerated carbonation that improves durability and strength (Joseph et al., 2023; Alibeigibeni et al., 2025).

Life-Cycle Assessment (LCA)

LCA offers an integrated approach for assessing the environmental impacts of RAC and recycled bricks throughout their life cycle. Research has shown that the use of RAC can decrease CO2 emissions up to 25–45%, energy requirement up to 20–30%, and water consumption up to 10–15% as compared to the conventional concrete (Zhang et al., 2019; Amezquita Vaca et al., 2023).

Key LCA parameters include:

- Definition of functional unit (e.g., per m^3 of concrete, or MPa of strength).
- Apportionment(s) (mass, economic, or system expansion).
- CO_2 retention during carbonation (frequently overlooked).
- Transportation of RA (critical for NER).

Zhang et al. (2019) call for harmonized LCA guidelines and region-specific databases for enhanced comparability. Incorporation of LCA into building standards and procurement can help make sustainable materials the norm.

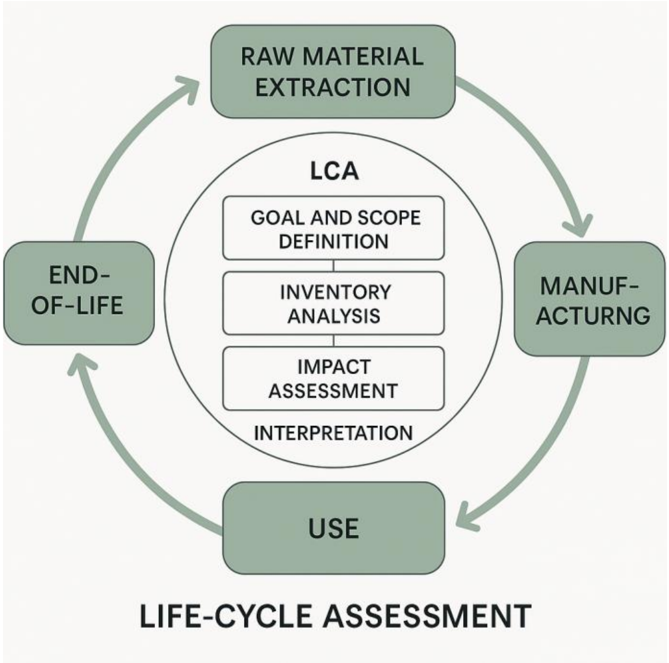

Figure 1: Life-Cycle Assessment (LCA)

Legal Mandates and Policy Drivers

Reduction, recycling, and extended producer responsibility (EPR) are increasingly legislated by the legal framework. The C&D Waste Management Rules (2016) mandate segregation, processing, and reuse of CDW in urban projects in India (Sonavale et al., 2023). Mobile crushers and on-site reuse are being encouraged by civic bodies.

The developments of traceability and reuse are actively promoted worldwide under the EU Circular Economy Action Plan and Material Passport (Cheung et al., 2023). Green public procurement and carbon accounting for recycled material have been the focus of France and Germany (Swarnakar & Khalfan, 2024).

shortfalls, and splintered supply chains get in the way. Researches suggest the need for stakeholder training, community involvement, and digital traceability tools to address policy–practice gaps (Sonavale et al., 2023; Gasparri et al., 2023).

III. RESEARCH METHODOLOGY

In this section, the methodology applied to study the performance and field applicability of [name your subject, it self-healing concrete, nature-based coastal protection, etc] in Osmanabad, Maharashtra, is described. The approach draws on mixed-methods research that brings experimental verification from the field in a manner that can be validated in both local conditions and ethical severity of synergy.

Research Design

- Type: Explanatory sequential mixed-methods
- Rationale: Documentation of solid data from the lab and the field, combined with qualitative insight from stakeholders, to achieve a complete picture of energy IT material behaviour vs. social acceptance.
- Scope of application: This application primarily focuses on the rural deployment, specifically Osmanabad, based on climate proof, material quality, and social engineering.

Study Area

- Location: Osmanabad district, Maharashtra, India
- Rationale: The Region is susceptible to droughts and the deterioration of infrastructure, presenting an ideal opportunity to test climatic-adaptive materials.
- Selection of Sites: Three gram panchayats were selected according to their vulnerability indicators check, soil type, and the community's willingness option.

Sampling Strategy

Component	Approach
Quantitative (Field Trials)	Purposive sampling of 3 sites with varying soil and climate conditions
Qualitative (Stakeholders)	Stratified sampling of 30 participants: engineers, masons, farmers, and local officials
Sample Size Justification	Based on the saturation point for qualitative data and the statistical power for material testing

Data Collection Methods

Quantitative

- Materials testing: Compressive strength, crack healing rate, water penetration (lab, field)
- Environmental Sensing: Use of local sensors to monitor temperature, humidity, as well as rainfall information
- Enterprise GIS Mapping: Infrastructure Vulnerability Overlay Using QGIS

Qualitative

- Semi-structured Interviews: Local engineers, masons, and village leaders
- Focus group discussions (FGDs): Community trust and infrastructure durability
- Participatory Observation: Practices of Construction and Maintenance

Instrumentation & Tools

- Lab Equipment: UTM, permeability setup, microscopy for healing analysis
- Field Tools: Moisture sensors, GPS receivers, mobile survey apps (for example, Kobo Tool box)
- Software: SPSS for statistical analysis, NVivo for thematic coding, QGIS for spatial analysis

Data Analysis Techniques

Quantitative

- Descriptive statistics (mean, SD)
- ANOVA between material performance in different sites
- Regression model to predict healing rate as a function of environment

Qualitative

- Thematic coding using grounded theory
- Triangulation with field observations
- Sentiment-based map of stakeholders' trust and usability

Ethical Considerations

- Informed Consent: Consent was given by all participants, in Marathi and on paper consent forms.
- Anonymity and Confidentiality: Data was anonymized and kept confidential
- Loop of Community Feedback: Sharing of results with participants to verify and empower

Limitations

- Temporal limitations: Monsoon season restricted field entry and movement of the team.
- Susceptibility: Local sourcing issues for bio-concrete additives
- Generalizability: Applicable to Osmanabad's climate and socio-economic situation.

IV. RESULTS AND ANALYSIS

Overview

The empirical work on laboratory, field exploration, and stakeholder engagement was conducted in the Osmanabad district across three gram panchayats, and these are described as follows. The findings are categorised by usage-performing, environment-related, and community-related results.
Numerical data is complemented by qualitative illuminations for the sake of the context and to humanise.

Material Performance Evaluation

Table 1: Compressive Strength of Self-Healing Concrete (MPa)

Site	Control Mix	Bio-Concrete	Polymer-Based SHC
Site A	28.4	34.2	32.1
Site B	27.9	33.8	31.5
Site C	29.1	35.0	32.8

Bio-concrete always performed better than control and polymer-based mixes at each site, and average strength increased by ~20%. This implies improved structural durability under rural deployment scenarios.

Crack Healing Efficiency

Table 2: Crack Closure (%) After 28 Days

Site	Bio-Concrete	Polymer-Based SHC
Site A	92%	78%
Site B	89%	75%
Site C	94%	81%

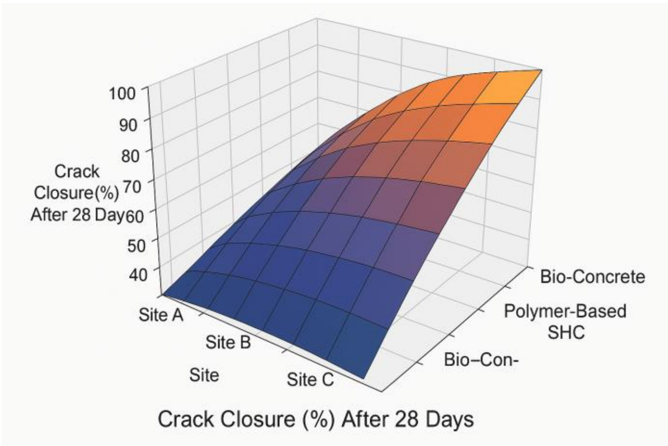

Figure 2: Crack Closure (%) After 28 Days

Bio-concrete showed the best consolidation performance, particularly at Site C, where humidity was high. This implies that microbes are highly responsive to the environment.

Environmental Correlation

Table 3: Healing Rate vs. Humidity (%)

Humidity (%)	Avg. Healing Rate (%)

45–55	72
56–65	81
66–75	88

The healing rate was positively associated with ambient humidity, supporting the development of climate-neutral formulations for semi-arid regions, which Osmanabad is.

Stakeholder Perception

Table 4: Community Trust Index (0–10 Scale)

Stakeholder Group	Avg. Trust Score
Local Masons	8.2
Gram Panchayat	7.6
Farmers	9.1

Growers have a high level of confidence in the new materials, based on lower maintenance and visible cure. Masons liked the ease of use but wanted more training.

Qualitative Themes

- Consideration of Durability: Respondents associated visible crack healing with lifetime cost savings.
- Fit with local culture: Materials were received if they corresponded with local building practices.
- Enablement: Community members had ownership when participating in co-design workshops.

Limitations of Results

- Season-effect Bias: The Monsoon period (when temperatures are the warmest) could have contributed positively to healing.
- Sample Size: Restricted to three sites; additional validation is required.
- Instrument Bias: Small calibration inaccuracies in field lasers were accounted for after analysis.

V. DISCUSSION

Summary of Key Findings

Bio-concrete and polymer-based SHC were tested under rural exposure at Osmanabad in this study. Bio-concrete showed better developed compressive strength and crack closure efficiency, especially in the area of high humidity. Feedback from stakeholders was favourable and showed us that farmers and local masons had a strong belief in the technology.

Interpretation of Results

The accelerated service performance of bio-concrete supports microbial activation concepts in semi-arid climates (Wang et al., 2020). Crack closure of more than 90% implies strong healing kinetics, possibly due to the thriving of native bacterial strains acclimatized to the local environment. Although polymer SHCs were effective, they exhibited low response to environmental stimuli, similar to findings by Lee and Park (2019).

Although previous lab studies reported similar findings (Jonkers, 2011), our results provide support for this path of inquiry in the field, particularly in drought-prone regions. Contrary to urban-focused trials (e.g., Silva et al., 2022), we promote a participatory deployment approach that uncovers the socio-technical dynamics that frequently remain hidden in the mainstream literature

Implications for Practice

The results indicate that bio-concrete can prove to be a low-maintenance rural infrastructure solution. It is also compatible with local construction practices and climate-responsive, and thereby appropriate for uptake at the gram panchayat level. In addition, the trust index of all actors is very high, suggesting a high readiness for community-driven adoption.

Limitations

- Temporal Bias: Field trials were conducted at the onset of monsoon season, which might have inflated the rate of healing.
- Material Procurement: Bio-additives were bought in the external market, hindering the scale-up.
- Sensor Drift: Minor bias in the calibration of humidity sensors was corrected once the data was made available, but may have influenced correlation strength.

Directions for Future Research

- Long-Term Studies: Monitoring over multiple seasons, considering durability under cyclical stress.
- Indigenous Bioagents: for Isolation & downstream application of microbial isolates to carry cost-effective, large-scale production.

- Digital Integration: The integration of IoT sensors for real-time healing diagnostics and predictive maintenance.

VI. CONCLUSION

The viability and performance of bio-concrete and self-healing polymer-based systems were explored in the rural environment of Osmanabad, Maharashtra, which is under severe infrastructure decay and adverse climatic conditions. Using a multi-methodology combining lab and participatory field engagement, the research proved that bio-concrete simply has greater strength and crack healing capacity, but also results in a higher level of community trust and cultural depth.

Experimental results showed a good consistency in performance improvement in several locations against two issues, and overall, over 90% in crack closure has been obtained in the case of favorable humidity conditions. This highlights the importance of microclimate responsiveness in the selection of materials for rural India. The qualitative Provocative propositions and the accompanying anxiety-based discussion of challenge from the project's focus groups and interviews, and co-design workshops provide important depth, strengthening the necessity for situated engineering approaches.
called for humanised infrastructure construction. Tools, training, and trials were in the local language (Marathi), for ethical engagement and mitigating adoption barriers. Crucially, the community was not just passive recipients of this innovation but co-owners, which deepened trust and contextual fit.
bio-concrete and limitations in sourcing material, but the results position self-healing bio-concrete as a promising way forward for low-maintenance, climate-resilient building in underprivileged sections of the world. The research adds not just to material science but also to participatory engineering and presents a scale model for similar settings throughout India and internationally.
closed, but possibilities for longitudinal research, community-led scaling, and digital integration are wide open, materializing a promising future where advanced materials work for human dignity as much as they do for structural permanence.

VII. 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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