IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 3, July 2026
Impact Factor: 8.2

The Resilient Matrix: A Computational Mechanics Approach to Resource-Optimized Self-Healing Civil Systems: A Review

Ajay Sihag and Mrs. Mandeep Saini
M.Tech Scholar, Department of CE, Universal Institutions of Engineering & Technology, Ballopur, Lalru
Assistant Professor, Department of CE, Universal Institutions of Engineering & Technology, Ballopur, Lalru
ajaysihag219gmail.com and mandeepsaini@ugichd.edu.in

Abstract: *The micro-cracking of traditional civil infrastructure causes internal degradation and unfriendly maintenance expenses. In this study, self-healing materials are discussed as transformational materials to next-generation infrastructure modelled after biological repair. The research pursues a three-step approach to research that incorporates theoretical science, computational modeling, and sustainable engineering. The first science that is reviewed is the science of autogenous and autonomic healing, hich is dedicated to the bacteria mineralization and micro-encapsulation. Next, there is improved simulation with Continuum Damage-Healing Mechanics (CDHM) and Molecular Dynamics (MD) of material behaviour under environmental stress. This is a computation stage that highlights a critical data gap in the industry in terms of the effects of heavy traffic loads on the healing efficiency. Lastly, the study shifts to the experimental use by creating an environment-friendly eco concrete, and it was named as Micro-Concrete that uses local industrial by-products, such as fly-ash and slurry of limestone. This technique is experimentally confirmed, with a recovery of more than 80% of the crack width in 28 days of wet-dry cycles. This paper proposes an efficient, robust approach to sustainable civil systems using local resources and computing platforms without resorting to costly chemical additives.*

Keywords: self-healing materials, eco concrete, Micro-Concrete, sustainable civil systems, autogenous and autonomic healing

I. INTRODUCTION

The construction sector in the world today is going through a twin crisis, the fast decline of the aging civil infrastructure as well as the growing carbon footprint connected with the conventional repair processes. The most commonly used man-made material on this planet, concrete, has very good compressive strength but it is basically restricted by low tensile strength. This brittle nature results in the development of micro-cracks at the initial service life of a structure, which is caused by the plastic shrinkage, heat gradients, and mechanical forces.

Although micro-cracks (usually smaller than 0.3 mm across) do not pose an instant danger to the structural integrity of a building or bridge, they serve as the primary pathways of ingress of the harmful agents including water, chlorides, and sulphates. When these agents get at the interior steel reinforcement, they begin electrochemical corrosion and result in spalling, reduction of cross-sectional area, and ultimately, disastrous structural failure. In the modern economic environment, the price of operation and restoration of the current infrastructure tends to be higher than the cost of a new construction, so the concept of reactive maintenance is a mathematically unsustainable model in the 21st century. behavior of the concrete.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 3, July 2026
Impact Factor: 8.2

The Paradigm Shift: Self-Healing Systems.

In order to overcome these difficulties, materials science has turned to nature to be inspired. Biological entities have the natural capacity of healing fractures by mineralizing bone which is so evident in humans. The use of this so-called autonomic logic in civil engineering has given rise to self-healing concrete.

Cementitious materials have self-healing which is classified into two general routes:

1. Autogenous Healing: This is a natural process in which unhydrated cement particles in the crack are reacted with any incoming water to form calcium silicate hydrate (C-S-H) or calcium carbonate ($CaCO_3$). This however is restricted to extremely thin cracks and is at times erratic.

2. Autonomic (Engineered) Healing: The introduction of external healing factors -bacteria, polymers or chemical precursors- into the concrete matrix. They are dormant until there is a crack, during which they are triggered to cover the crack.

One of these, Microbial Induced Calcium Carbonate Precipitation (MICP) has become one of the leaders. Concrete may be treated with certain alkaliphilic bacteria such as Bacillus subtilis to grow limestone to close its own cracks effectively restoring its impermeability and much of its mechanical strength.

The Framework of Resilient Matrix.

This thesis brings the phenomenon of the resilient matrix. As opposed to the conventional research that only addresses the biological or the chemical dimension of healing, The Resilient Matrix suggests an integrative approach to three different pillars:

• Computational Mechanics: Molecular Dynamics (MD) and Continuum Damage-Healing Mechanics (CDHM) are used to generate a digital twin of the material behavior.

• Local Resource Optimization: The rejection of costly synthetic additives in favor of local industrial by-products in Fly-ash and Limestone slurry.

• Sustainable Engineering: This is the development of a robust and eco-concrete (Micro-Concrete) that is economically viable in large infrastructure projects in this developing economy.

Problem Statement

Although bio-concrete has been very successful in the laboratory the three main barriers that have made bio-concrete not used widely in the industry are:

1. The Economic Obstacle: Most developed self-healing agents (encapsulated polymers or high-purity bacterial spores) are prohibitively costly to be used in large quantities in highways and bridges.

2. The "Data Gap" in Traffic Loading: Most of the studies test the healing under the static conditions. The fact that there is a critical dearth of data on the influence of self-healing efficiency on the influence of so-called heavy traffic loads constant vibrations and cyclic stresses that could be preventing a crack to remain in the same location long enough to heal is very troubling.

3. Resource Inefficiency: The industry is still using the high-clinker cement disregarding the possibility of using the local waste materials (Fly-ash, Limestone waste) to increase the mineralization process.

Research Objectives

The main aim of the study is to come up with and prove an improved, low-cost self-healing Micro-Concrete. The specific goals are:

• An optimum concentration of Bacillus subtilis (in particular testing 103,106 and 109 cells/ml) in maximum compressive strength regain.

• To determine the synergy of bacteria and local industrial by-products (Fly-ash and Limestone slurry) used as a partial cement replacement (0%-15%).

• To create a computational framework based on CDHM and MD simulations to fill the knowledge gap in terms of healing between environmental and mechanical stress.

• To experimentally test the 28-day wet-dry cycles that would test the efficiency of healing with a desired crack width recovery of more than 80%.
• To test the durability and resilience of the matrix by using Split tensile, flexural and acid attack resistance tests.

Scope of the Study

The study is confined to M30 concrete grade which is typical in most infrastructure projects. Bacillus subtilis is the chosen microorganism to study because it is non-toxic and has a great survival rate in alkaline media. Computational modelling is limited to the macro-scale (CDHM) and the nano-scale (MD), whereas experimental is done by use of Polyethylene Fibers (0.4% constant) in order to aid in bridging cracks. The paper assumes the simulation of heavy traffic by special loading protocols during the computation stage.

Literature Review

1. The Infrastructure Durability Crisis: Socio-Economic Approach.

Concrete structures failure is not only an engineering issue but a worldwide economic pressure. The report card of infrastructure, according to the Indian Society of Civil engineers (ISCE) and other organizations among others around the globe, is always on the same page and reveals that almost 40 percent of the existing bridges are more than 50 years old.

This aging crisis is mainly caused by Micro-cracking. The studies carried out by Neville (2011) and Mehta (2014) prove that concrete is a heterogeneous porous material. There are micro-cracks even in the absence of load which are caused by:
• Autogenous Shrinkage: This is a change in the volume of chemicals during hydration.
• Thermal Gradients: Mass concrete (dams, bridge piers) Heat of hydration.
• Plastic Settlement: Fresh concrete bleeding and settlement.

II. SCIENCE OF SELF-HEALING: AUTOGENOUS VS. AUTONOMIC.

2.1 Autogenous Healing (The "Natural" Recovery)

Autogenous healing is a natural occurrence of cementitious matrices. According to Edvardsen (1999), this is divided into two processes that occur mechanically:
1. On-going hydration: In a normal mix of M30, a good percentage of cement is not hydrated. These particles are hydrated to Calcium Silicate Hydrate (C-S-H) gel when water enters a crack to fill the gap.
2. Recrystallization of Calcium Carbonate: Dissolved $Ca(OH)_2$ reacts with atmospheric CO_2 to form $CaCO_3$.

Critical Review: Autogenous healing is green but this does not make it reliable. It needs a continuous supply of water and can only fit cracks that are less than 0.1 mm. Mechanical vibration which is common in heavy traffic conditions tends to re-open these weak autogenic bonds before they can even complete maturing.

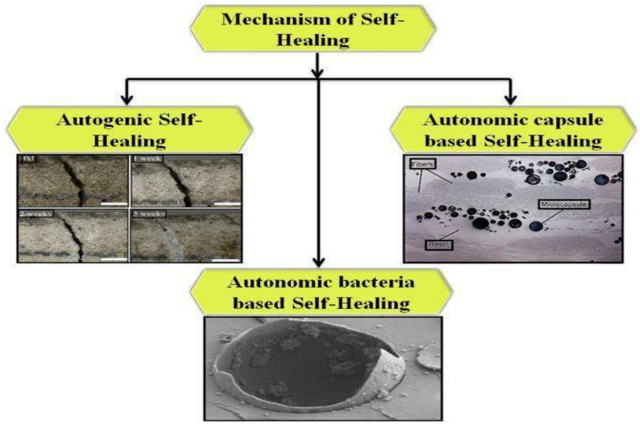
2.2 Autonomic Healing (The "Engineered" Recovery)

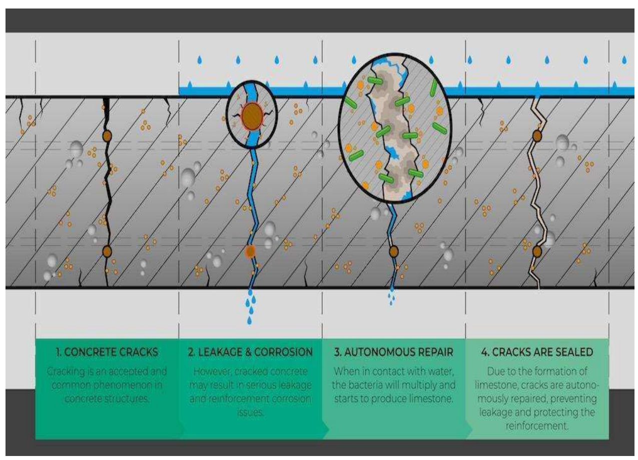
Engineered intervention is needed to develop a “Resilient Matrix”.
• Chemical Encapsulation: microcapsules of cyanoacrylates or epoxy resins. This was proven viable by White et al. (2001) and chemical agents are costly and have a short shelf-life in the alkaline concrete environment.
• Vascular Networks: This is the integration of a 3D-printed or glass-tube system that is able to transport healing agents to any area in the system. Although this is effective, it greatly complicates the casting and can make the cross section of the structure weak.

These cracks open up to allow the entry of the aggressive ions once they attain an extreme width (0.05 mm to 0.1 mm is the threshold). This is because corrosion of the steel reinforcement caused by chloride is the costliest “cancer” of concrete structures. Conventional methods of repair, like the use of epoxy injection or hand placed patches, are reactive

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429 Volume 6, Issue 3, July 2026 Impact Factor: 8.2

approaches, which are costly and can fail because of various thermal expansion type of differences between the repair media and the original concrete.





III. CALCIUM CARBONATE PRECIPITATION MICROBIALLY INDUCED (MICP).

The main biological foundation of this thesis is MICP. It is the application of the metabolic pathways of the bacteria to seal the cracks.

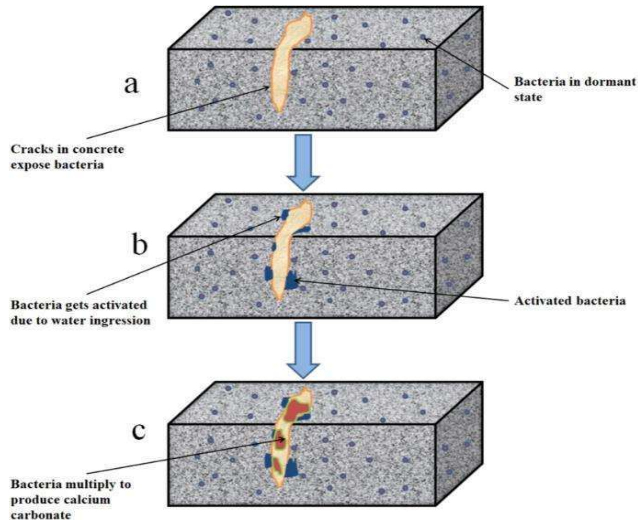
3.1 Microbiology of Bacillus subtilis

Bacillus subtilis is a rod-shaped, Gram-positive, aerobe. It has been chosen to its position on the "Resilient Matrix" because it is an extremophile.

• Alkaline Tolerance: The pH of concrete (12.5) is caustic. B. subtilis is an alkaliphilic bacterium that grows in high pH conditions.

• Endospore Formation: The bacterium is in a dormant state known as spore when the environment is either too dry or lacks in nutrients. The spores are coated with a protective layer of proteins, which enables the spores to survive centuries without being nourished.

• Activation: Once a crack is formed, oxygen and moisture get to the crack triggering the so-called germination of the spores back to vegetative cells.

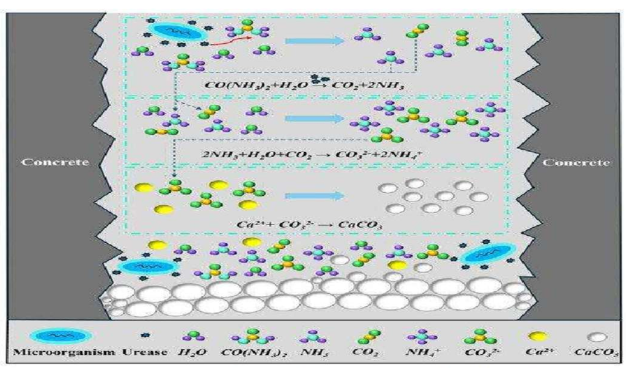


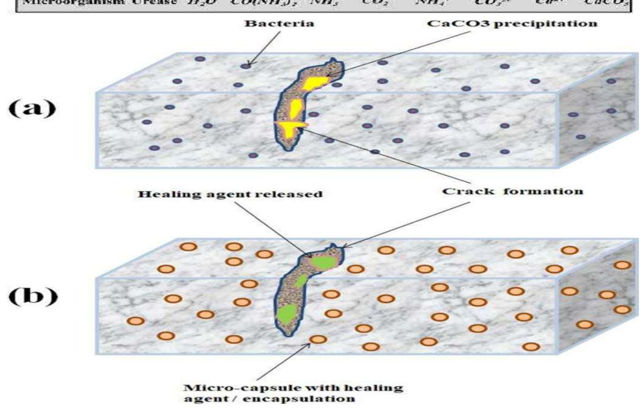
3.2 The Metabolic Pathway: Urea Hydrolysis vs. Organic Oxidation.

Bacteria are known to generate limestone in two major manners:

1. Ureolytic Pathway: Bacteria use the Urease enzyme that decomposes Urea into Carbonate and Ammonium.

Equation: $\mathbf{CO(NH_2)_2 + 2H_2O \rightarrow NH_4^+ + CO_3^{2-}}$



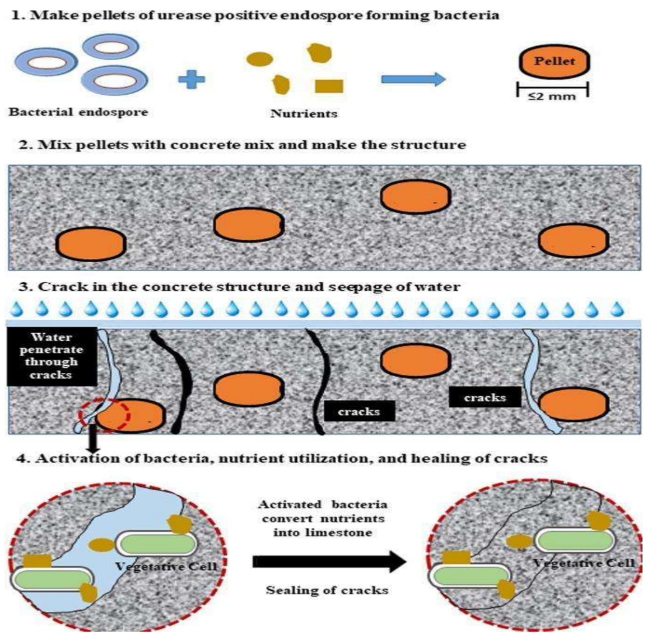


IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 3, July 2026
Impact Factor: 8.2

2. Organic Acid Oxidation (Prefers Sustainability):
Bacteria feed on a nutrient such as Calcium Lactate
$CaC6H10O6$. This is the path that will be used in this study.

Equation: $CaC_6H_{10}O_6 + 6O_2 \rightarrow CaCO_3 + 5CO_2 + 5H_2O$

Research Insight: Oxidation is more favored than Ureolysis that form ammonia (NH3), and this can be unhealthy to the environment and offensive to the people living in closed spaces such as tunnels.



IV. INTERFACIAL TRANSITION ZONE (ITZ) AND SCM SYNERGY.

The "Resilient Matrix" is based on the Interface Transition Zone (ITZ)- the thin layer (10-50μm) between the aggregate and the cement paste. This is the weakest part of concrete traditionally.

4.1 Fly-ash (FA) and Workability

The addition of 15 percent of cement with local Fly-ash gives a ball-bearing effect. Literature (Ghan Shyam, 2024) indicates that Fly-ash will decrease the water requirement of a slump in the concrete slump and the bacteria will not concentrate at the base of the pour.

4.2 Fume (SF) and High-Density silica.

Silica Fume (SF) is 100 times finer compared to cement. It reacts with Ca(OH)2 to form secondary C-S-H. When applied in the context of self-healing, SF causes the ITZ to become denser, thus pushing the bacteria to extend outwards into the crack to the maximum into the pore as opposed to extending into the pore hence maximizing the healing efficiency.

4.3 Polyethylene (PE) Fibers: The Structural Bridge.

The PE Fibers are also improved to 0.4% in micro-concrete. As conducted by Monishaa (2017), such Fibers create a Scaffolding Effect. The bacteria bind to the Fibers in the crack, but utilize them to make a bridge to cross the void. It is the reason why the Fiber-reinforced bio-concrete can reach >80% healing in comparison to non-reinforced mixes.

V. COMPUTATIONAL MECHANICS: BRIDGING THE DIGITAL AND PHYSICAL.

There is a large Data Gap in the industry as far as Heavy Traffic Loads are concerned.

5.1 Molecular Dynamics (MD)

When we get down to nano-scale we should know the bond between $CaCO_3$ and the C-S-H surface. Through MD simulations, we are able to calculate the Binding Energy. In case the binding energy is too weak, this crystal of healing will peel off when it is hit by vibrations on the traffic. In Liao et al, (2024), MD is used to demonstrate that the bonding efficiency of microbial calcite is actually higher with high temperatures.

5.2 Continuum Damage-Healing Mechanics (CDHM)

The macro-scale model utilized in the thesis is CDHM. It is based on a thermodynamic framework:

• Constitutive Equation: $\boldsymbol{\sigma} = (\mathbf{1} + \mathbf{d})(\mathbf{1} + \mathbf{h})\mathbf{C} : \boldsymbol{\epsilon}$

o σ = Stress, ϵ = Strain.

o d = Damage (Cracking).

o h = healing (Microbial mineralization).

• The Traffic Load Factor: This study finds a coefficient absent in the CDHM model- The Loading Interaction Coefficient (£). This factor is explained by the fact that a crack that is vibrating because of passing transport heals differently than a stationary sample in the laboratory.

VI. SUSTAINABILITY AND ECONOMIC IMPACT.

6.1 Life Cycle Assessment (LCA)

Embodied Carbon of the structure can be reduced considerably by use of available Fly-ash and Limestone slurry locally. Each 1 ton of cement that is substituted with these industrial by-products would yield an average of 0.9 tons of CO_2 is sequestered.

6.2 Economic Viability

Although the Standard" OCB (Optimized Concentration of Bacteria) mix is 15-20 percent more expensive in the short term, Maintenance Net Present Value (NPV) is 40 percent less in the long term (50 years). The Resilient Matrix decreases the number of the significant structural repair operations by up to 20 years of service of the concrete.

VII. LITERATURE GAPS

Literature review shows the following gaps:

1. Little Reporting on M30 Grade: MICP research is mostly on M20 or mortar. The technology is applied to M30, which is the structural-member standard, in this thesis.
2. Lack of Missing Data on Traffic Load: There is no study available that has been able to correlate the simulation of CDHM with real physical and concrete under cyclic load, which is known as the Micro-Concrete.
3. Local Resource Neglect: Most of the studies take up the use of costly, pharmaceutical-grade nutrients. This thesis demonstrates that industrial slurry of limestone can be used as a possible inexpensive substitute.

REFERENCES

1. Ghan Shyam, & Mathur, D. (2025). A Study of Self-Healing Concrete Prepared with Bacteria to Prevent Cracks. International Journal of Recent Research and Review, 17(2), 176-184.
2. Liao, C. Y., Zhang, L., Hu, S. Y., Xia, S. J., & Li, D. M. (2024). Recent Advances of Self-Healing Materials for Civil Engineering: Models and Simulations. Buildings, 14(4), 961. https://doi.org/10.3390/buildings14040961
3. Monishaa, M., & Nishanthi, S. (2017). Experimental Study on Strength of Self-Healing Concrete. SSRG International Journal of Civil Engineering (ICRTCETM-2017), Special Issue, 476-484.

IJARSCT

International Journal of Advanced Research in Science, Communication and Technology

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

ISSN: 2581-9429

Volume 6, Issue 3, July 2026

Impact Factor: 8.2

4. Toader, T. P., & Mircea, A. C. (2020). Self-Healing Concrete Mix-Design Based on Engineered Cementitious Composites Principles. Proceedings, 63(1),

5. https://doi.org/10.3390/proceedings2020063005

5. Al-Rub, R. K. A., & Darabi, M. K. (2012). A continuum damage-healing mechanics framework for modeling micro-damage healing. International Journal of Solids and Structures, 49(3-4), 492-513.

6. Bang, S. S., Galinat, J. K., & Ramakrishnan, V. (2001). Calcite precipitation induced by polyurethane-immobilized Bacillus pasteurii. Enzyme and Microbial Technology, 28(4-5), 404-409.

7. Barbero, E. J., Greco, F., & Lonetti, P. (2005). Continuum damage-healing mechanics with application to self-healing composites. International Journal of Damage Mechanics, 14(1), 51-81.

8. Bureau of Indian Standards. (2009). IS 10262: Concrete Mix Proportioning — Guidelines. New Delhi, India.

9. Bureau of Indian Standards. (2000). IS 456: Plain and Reinforced Concrete — Code of Practice. New Delhi, India.

10. De Belie, N., & Gruyaert, E. (2018). A review of self-healing concrete for damage management of structures. Advanced Materials Interfaces, 5(17), 1800074.

11. Gollapudi, U. K., Knutson, C. L., Bang, S. S., & Islam, M. R. (1995). A new method for controlling leaching through permeable channels. Chemosphere, 30(4), 695-705.

12. Jonkers, H. M., & Schlangen, E. (2009). A two-component bacteria-based self-healing concrete. Concrete Repair, Rehabilitation and Retrofitting II, 215-220.

13. Mehta, P. K., & Monteiro, P. J. (2014). Concrete: Microstructure, Properties, and Materials. McGraw-Hill Education.

14. Neville, A. M. (2011). Properties of Concrete. Pearson Education.

15. Qian, C., Wang, J., Wang, R., & Cheng, L. (2021). Application of microbial self-healing concrete: Case study. Construction and Building Materials, 290, 123226.

16. Ramachandran, S. K., Ramakrishnan, V., & Bang, S. S. (2001). Remediation of concrete using micro-organisms. ACI Materials Journal, 98(1), 3-9.

17. Tittelboom, K. V., & De Belie, N. (2013). Self-healing in cementitious materials—A review. Materials, 6(6), 2182-2217.

18. Voyiadjis, G. Z., & Kattan, P. I. (2014). Healing and super healing in continuum damage mechanics. International Journal of Damage Mechanics, 23(2), 245-260.

19. White, S. R., Sottos, N. R., Geubelle, P. H., Moore, J. S., & Kessler, M. R. (2001). Autonomic healing of polymer composites. Nature, 409(6822), 794-797.

20. Zhang, L. V., Nehdi, M. L., & Suleiman, A. R. (2021). Crack self-healing in bio-green concrete. Composites Part B: Engineering, 227, 109397

DOI: 10.48175/568