SELF-HEALING CONCRETE: A COMPREHENSIVE REVIEW OF STRENGTH, DURABILITY AND HEALING AGENTS

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Abstract: Self-healing concrete is an innovative material designed to repair its own cracks, thereby enhancing durability, reducing maintenance costs, and extending the lifespan of concrete structures. This technology addresses one of the most significant challenges in civil engineering crack formation due to mechanical loads, environmental effects, and shrinkage. Various self-healing mechanisms have been developed, including autogenous healing, capsule-based systems, vascular networks, and microbial-induced calcite precipitation. Each method has shown promising results under laboratory conditions, yet faces challenges in terms of scalability, cost, environmental impact, and performance consistency in real-world applications. This review critically examines the latest advancements in self-healing concrete, categorizing technologies based on healing agents, activation mechanisms, and effectiveness. It also explores the integration of these systems into conventional concrete and highlights key performance metrics such as crack width closure, recovery of mechanical properties, and durability enhancement. Finally, the review outlines current limitations, standardization needs, and future research directions to accelerate the adoption of self-healing concrete in the construction industry. These review papers employ a systematic and thematic approach to collect, analyzes, and synthesize scholarly literature on self-healing concrete. The objective is to understand the evolution, mechanisms, performance, and challenges associated with self-healing technologies in cement-based materials.

Keywords: Self-healing, Crack repair, Healing agent, Smart concrete, Healing efficiency, cementitious materials, Bio-concrete, Structural durability.

I. INTRODUCTION

Concrete is the most widely used construction material in the world, owing to its versatility, strength, and affordability. However, it is inherently brittle and prone to cracking due to factors such as thermal fluctuations, shrinkage, mechanical stress, and environmental exposure. Cracks not only compromise the structural integrity of concrete elements but also allow the ingress of harmful substances like water, chlorides, and carbon dioxide, which can accelerate deterioration through processes like corrosion of reinforcement and freeze-thaw damage. Conventional maintenance and repair techniques are often labour-intensive, expensive, and environmentally unfriendly. In response to these challenges, the concept of self-healing concrete has emerged as a sustainable and intelligent solution. Inspired by biological systems, self-healing concrete has the ability to autonomously repair cracks without external intervention, thereby restoring its mechanical and durability properties. Various self-healing strategies have been developed, including autogenous healing, where unhydrated cement particles react with moisture; encapsulated healing agents that are released upon cracking; vascular systems that transport healing materials through embedded networks; and microbial-based techniques where bacteria precipitate calcium carbonate to seal cracks. The incorporation of self-healing technologies into concrete presents significant potential to reduce maintenance costs, extend service life, and improve the sustainability of infrastructure. However, despite notable progress in laboratory research, practical implementation remains limited. Challenges such as the cost of healing agents, compatibility with concrete mix designs, reliability under varying environmental conditions, and lack of standard testing protocols hinder widespread adoption. This review paper aims to provide a comprehensive overview of self-healing concrete technologies, examining their mechanisms, effectiveness, and real-world applicability. By highlighting the current state of research, performance assessment techniques, and technological limitations, this paper intends to guide future research efforts and support the transition of self-healing concrete from laboratory innovation to mainstream construction practice.

2.METHODOLOGY:

The comprehensive review by De Belie etal. (2018) in Advanced Materials Interfaces examines advancements in self-healing concrete, an innovative material designed to autonomously repair cracks and damage in structural elements, thereby enhancing durability, service life, and sustainability. The review aims to evaluate the scientific principles, experimental validations, and practical potential of various self-healing mechanisms—including autogenous healing, encapsulated healing agents, vascular networks, and microbial-induced calcium carbonate precipitation—with a focus on improving structural longevity and reducing maintenance costs. Using a systematic literature review method, the authors compile and critically analyze data from laboratory experiments, field trials, and case studies to assess chemical, mechanical, and durability performance. The results show that self-healing concrete can effectively seal micro- and macro-cracks, restore mechanical strength, and reduce permeability, with microbial-induced precipitation and encapsulated agents performing particularly well in both controlled and small-scale field settings.

3. LITERATURE REVIEW:

1. De Belie et al. (2018) brief about the self-healing concrete, considering Advanced Materials in concrete Interfaces examines advancements in self-healing concrete, an innovative material designed to autonomously repair cracks and damage in structural elements, thereby enhancing durability, service life, and sustainability. The review aims to evaluate the scientific principles, experimental validations, and practical potential of various self-healing mechanisms—including autogenous healing, encapsulated healing agents, vascular networks, and microbial-induced calcium carbonate precipitation—with a focus on improving structural longevity and reducing maintenance costs. Using a systematic literature review method, the authors compile and critically analyze data from laboratory experiments, field trials, and case studies to assess chemical, mechanical, and durability performance. Author get the results which shows, the self-healing concrete can effectively seal micro- and macro-cracks, restore mechanical strength, and reduce permeability, with microbial-induced precipitation and encapsulated agents performing particularly well in both controlled and small-scale field settings

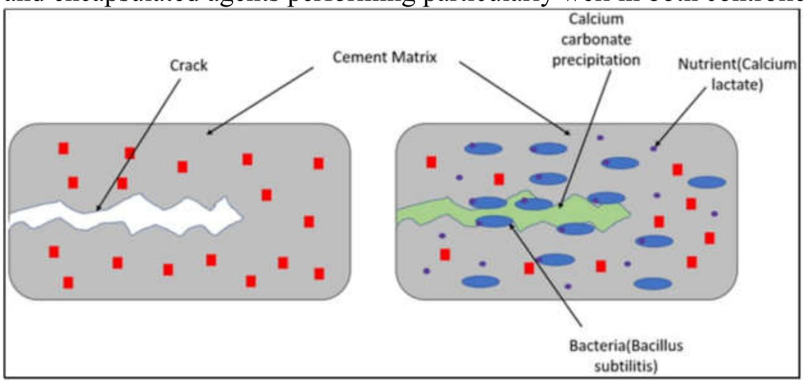


Fig:- Microbial Self-Healing Concrete

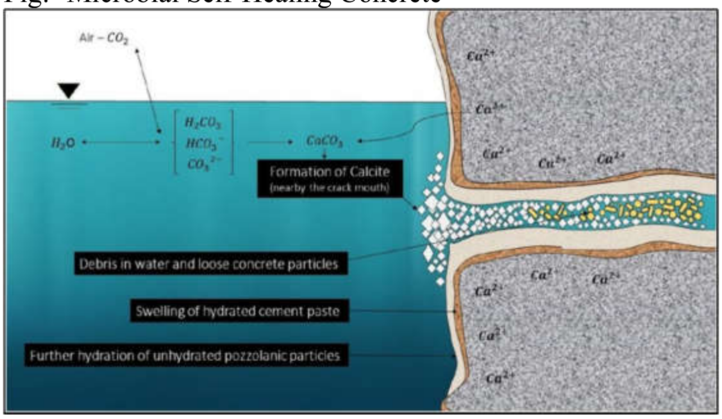


Fig:- Mechanism of Autogenous Self-Healing In Concrete

2. Microbial-Induced Calcium Carbonate Precipitation (MICP) in Concrete: A Review of Bacterial Species and Mechanisms — Grino, Al-Mashaqbeh, and Jonkers (2020) reviewed how certain bacteria can help repair concrete by producing calcium carbonate, a natural mineral that fills and seals cracks. This process, known as microbial-induced calcium carbonate precipitation (MICP), involves species such as Sporosarcina pasteurii and various Bacillus strains that generate minerals through metabolic activity. The aim of the study is to analyze bacterial mechanisms, identify suitable species, and evaluate environmental and operational factors affecting MICP efficiency. Using a comprehensive literature review method, the authors compiled experimental findings from lab and field studies to assess crack-healing performance. The results show that MICP can effectively seal cracks, reduce permeability, and enhance the durability of concrete, with performance influenced by parameters such as temperature, nutrient availability, and curing conditions. The review concludes that MICP is a promising, eco-friendly technique to extend the service life of concrete structures and reduce maintenance needs.

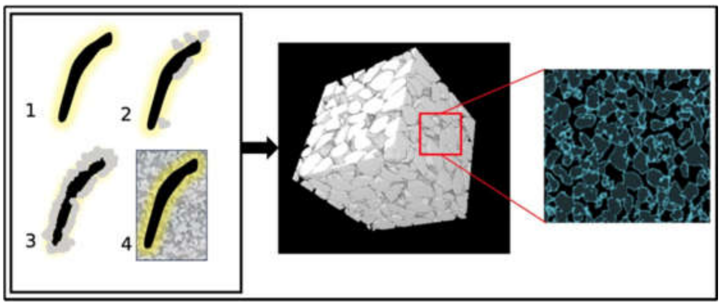


Fig:-Granular, Porous & Microstructural Analysis

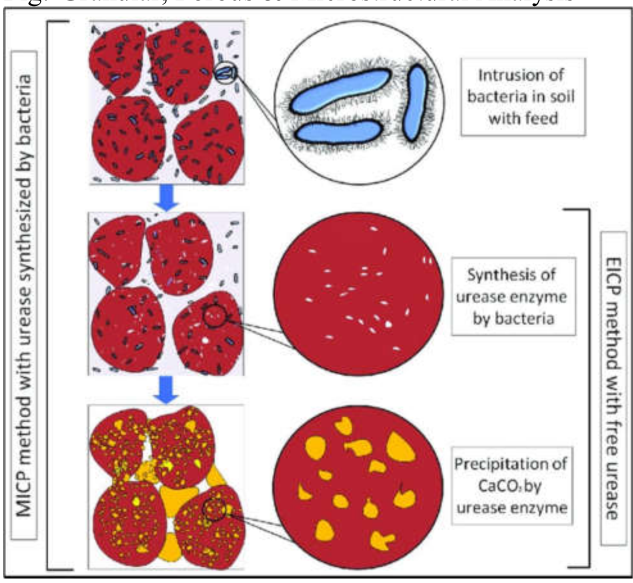


Fig:-Microbiologically Induced Calcite Precipitation

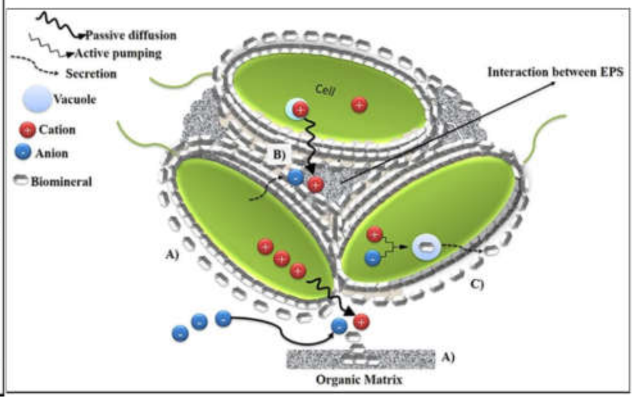


Fig:- Microbiologically Induced Calcium Carbonate Precipitation

3. A Bibliometric and Visual Analysis of Self-Healing Concrete Research (1974–2020) — Zhu, Yu, and Zhang (2021) conducted a comprehensive study of research on self-healing concrete published between 1974 and 2020, aiming to identify key trends, topics, and developments in the field. The authors used bibliometric analysis combined with visual mapping tools to examine thousands of published papers, tracking contributions from different countries, researchers, and institutions, as well as identifying the most studied themes and the growth of research interest over time.

The analysis revealed that self-healing concrete has become a rapidly expanding research area, especially in the last decade, with strong global contributions and increasing focus on repair mechanisms using capsules, bacteria, and special additives.

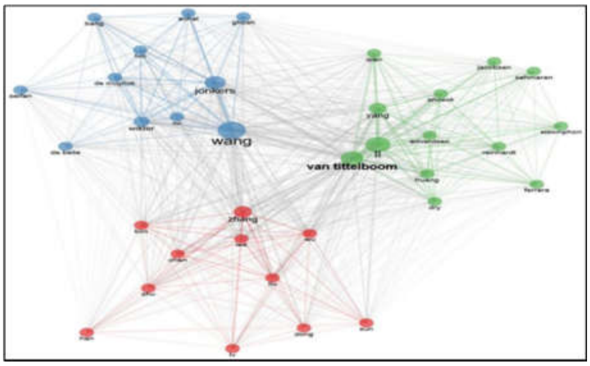


Fig: -Co-Citation Network

4. Modeling and Simulation Approaches for Self-Healing Concrete, Snoeck and De Belie (2019) reviewed various computer-based modeling techniques developed to understand and predict the behavior of self-healing concrete. A systematic literature review of existing modeling approaches including mechanical models, chemical reaction models, and multi-scale models was conducted, comparing their capabilities in predicting material behaviour.

The review found that each model type offers specific strengths mechanical models excel at simulating crack propagation, chemical models capture healing reactions, and multi-scale models integrate different physical processes but none alone can fully describe self-healing behaviour.

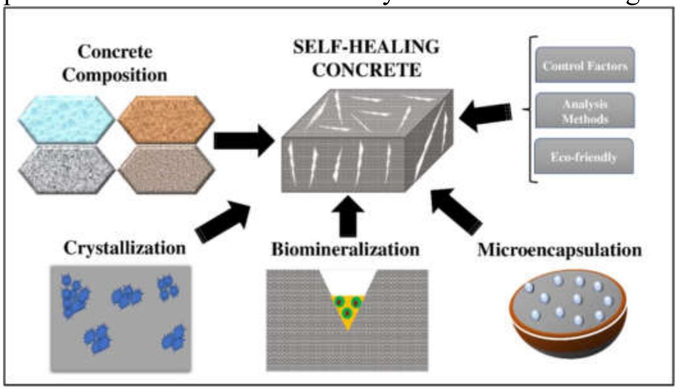


Fig:- Self-Healing Concrete

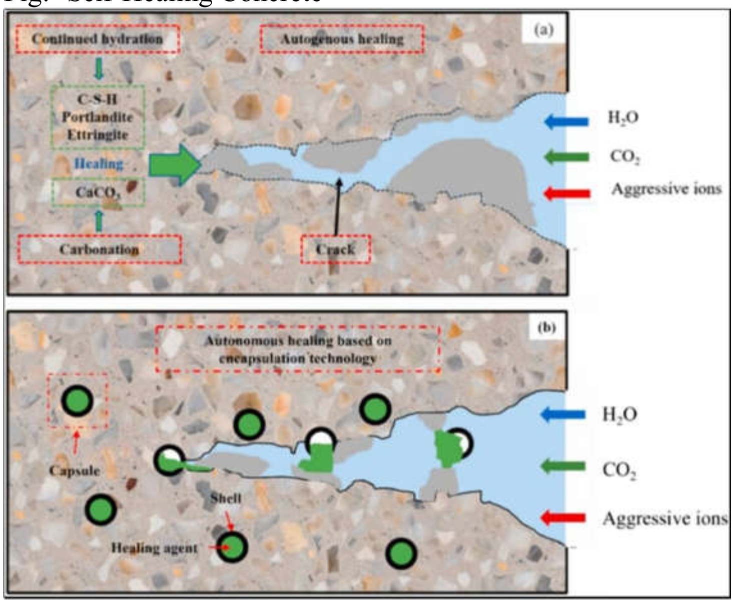


Fig:- Autonomous Healing Based on Encapsulation Technology

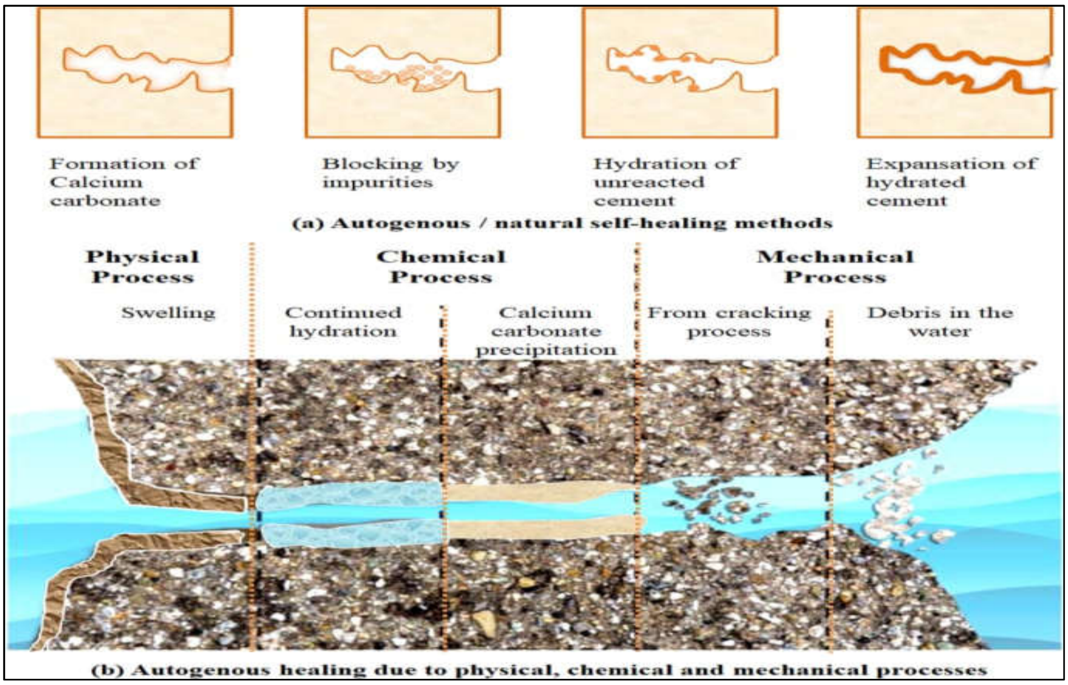


Fig:- Autogenous Healing Due To Physical, Chemical and Mechanical Processes

5. Low-Carbon Self-Healing Concrete: A Sustainable Solution for the Construction Industry examined the potential of combining low-carbon materials with self-healing techniques to create eco-friendly, durable concrete. A comprehensive literature review of studies on low-carbon materials and self-healing technologies was conducted, analyzing their environmental benefits and structural performance. The findings indicate that integrating waste-based, low-carbon binders with self-healing agents can significantly extend concrete's service life, lower maintenance needs, and reduce carbon emissions associated with repairs.
6. Self-Healing of Engineered Cementitious Composites (ECC) under Wet–Dry Cycles — *Li, V.C. and Herbert (2012)* investigated how engineered cementitious composites, a flexible and crack-resistant form of concrete, can self-heal when subjected to alternating wet and dry conditions. Experimental testing was conducted by exposing ECC specimens with pre-formed micro-cracks to repeated wet–dry cycles and analyzing crack closure and the formation of healing products. The study found that water exposure promoted the precipitation of healing compounds such as calcium carbonate, effectively sealing cracks and restoring durability.

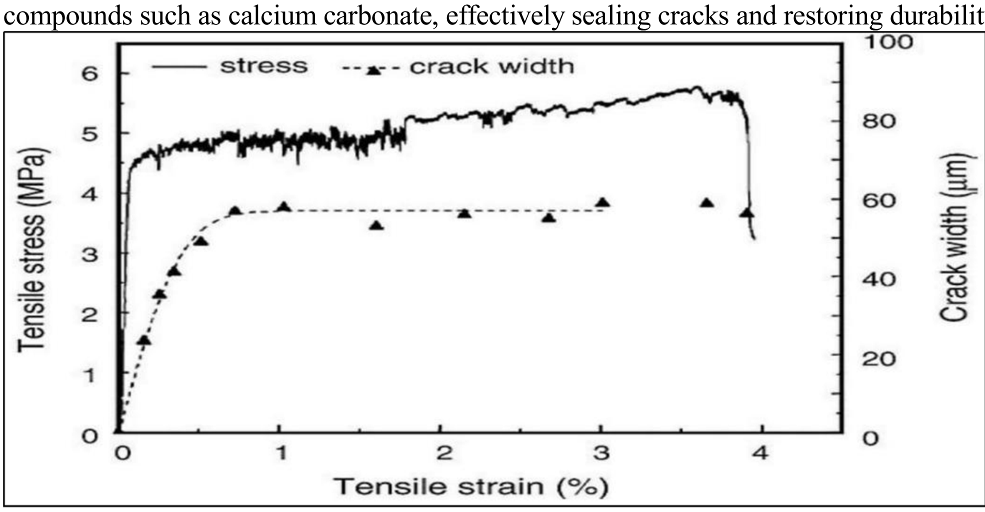
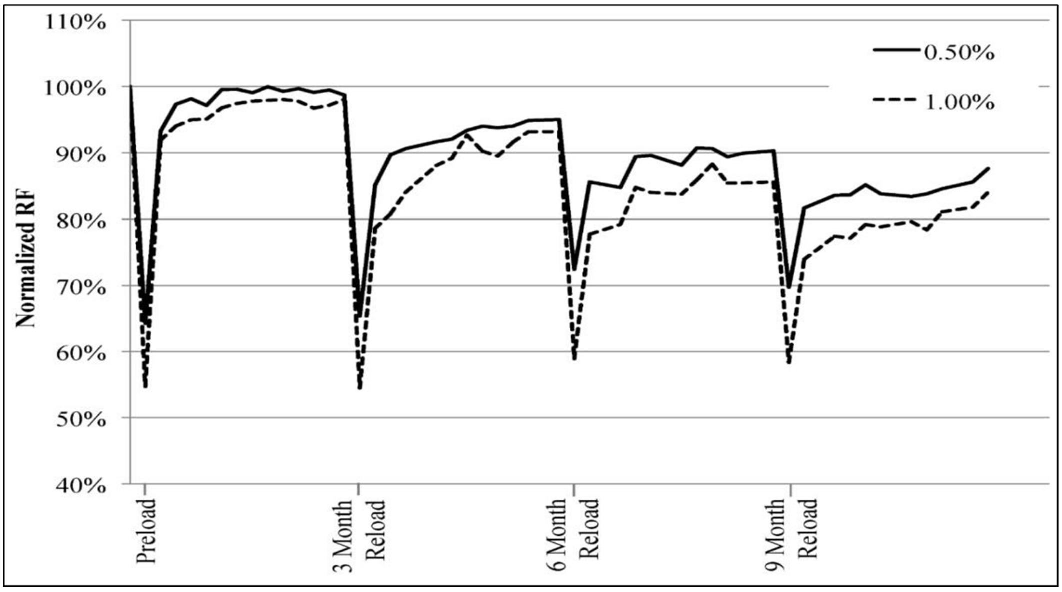


Fig:- Stress-Strain Relationship



7. Factors Influencing the Performance of Bacteria-Based Self-Healing Concrete — *Luo, Qian, and Li (2017)* investigated the key factors that determine the effectiveness of bacteria-based self-healing concrete in repairing cracks. Laboratory experiments were conducted using different bacterial strains, varying nutrient dosages, and controlled environmental conditions to measure healing efficiency. Results: The study found that healing performance improved with optimal bacterial selection, sufficient nutrient supply, smaller crack widths, and favourable temperature and moisture conditions.

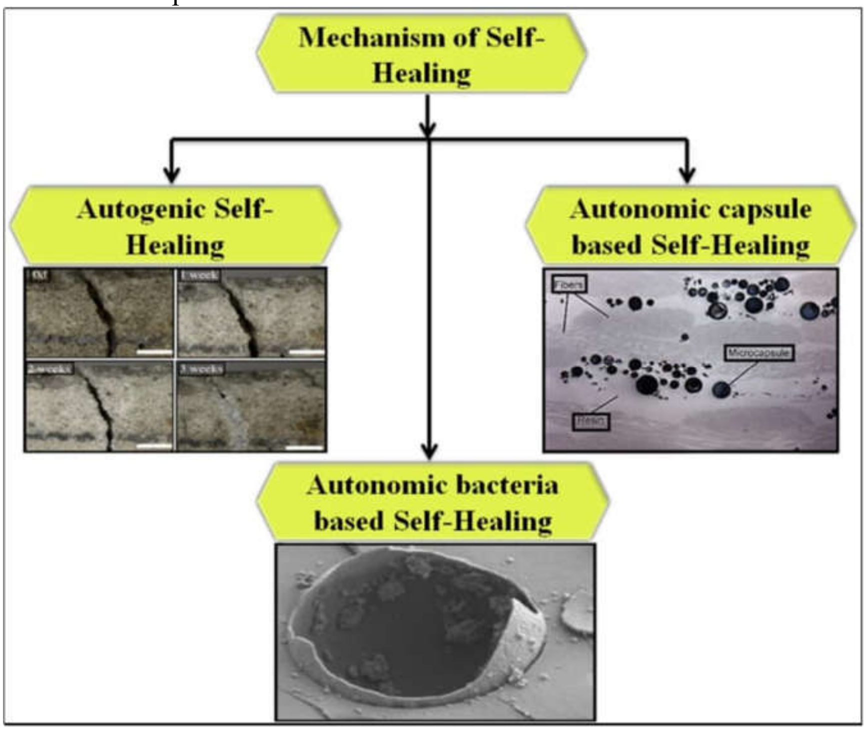
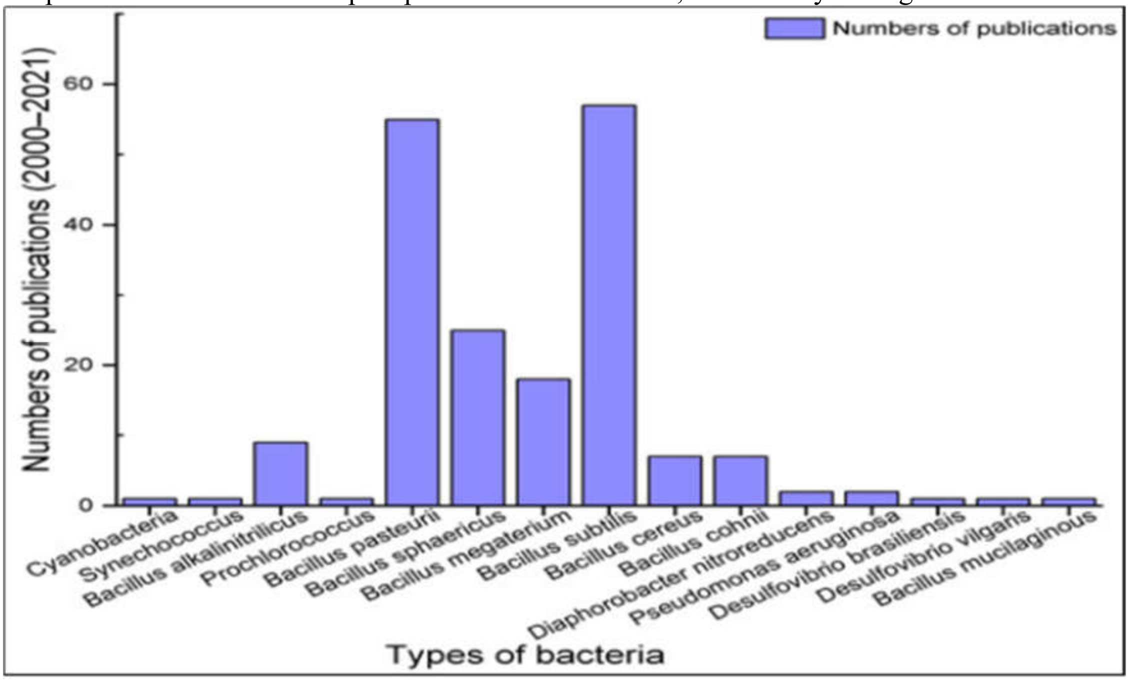


Fig:- Mechanism of Self-Healing

8. Exploring Fungi as a Self-Healing Agent in Concrete Menon, Radhakrishnan, and Arnepalli (2017) investigated the potential of fungi to serve as a self-healing mechanism in concrete. Laboratory experiments were conducted by incorporating different fungal strains into concrete samples and monitoring their growth, survival, and mineral precipitation capabilities. The study found that certain fungi can survive within concrete and produce calcium carbonate, effectively sealing cracks. The findings indicate that fungi-based self-healing systems could offer a promising, eco-friendly alternative for enhancing concrete durability.

9. High-Temperature Performance of Bacteria-Based Self-Healing Concrete Using Spor sarcina pasteurii Mirshah

mohammadi, Ramezanianpour, and Kazemi (2023)* investigated the effectiveness of the bacterium Sporosarcina pasteurii in self-healing concrete under elevated temperature conditions. Laboratory experiments were conducted by exposing concrete specimens containing S. pasteurii to varying high temperatures, then assessing bacterial survival, calcium carbonate production, and crack-healing performance. The bacteria remained viable at elevated temperatures and continued to precipitate calcium carbonate, successfully sealing cracks.



10. Enhancing Concrete Durability through Microbial Mineral Precipitation Achal, Mukherjee, and Reddy (2011) investigated the use of microbes to improve the long-term performance of concrete structures. Laboratory experiments were conducted by integrating selected bacterial strains into concrete specimens and monitoring their ability to survive, precipitate minerals, and repair cracks under controlled conditions. The findings showed that microbial concrete could successfully fill cracks with calcium carbonate, leading to improved strength, reduced permeability, and extended service life of structures

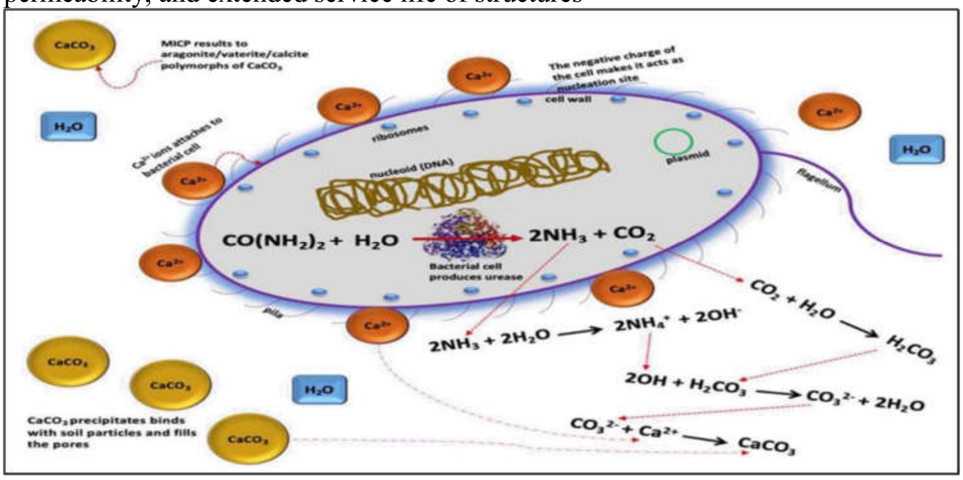


Fig:- Microbially Induced Calcite Precipitation

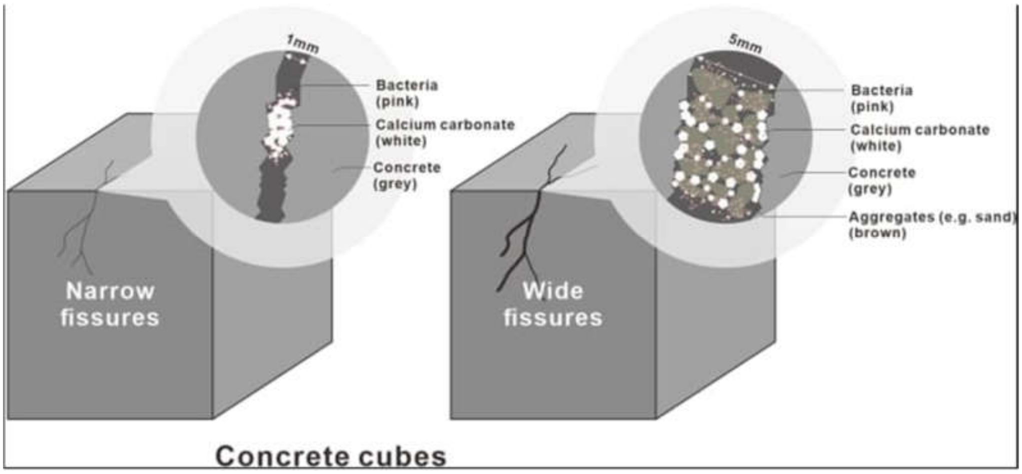


Fig:-Bio-Concrete Crack Repair

11. Microbial Calcium Carbonate Precipitation for Crack Repair in Construction Materials De Muyncks, De Belie, and Verstraete (2010) reviewed the potential of using microbes to produce calcium carbonate within construction materials for crack repair and strength enhancement. A comprehensive literature review of laboratory and field studies was conducted, analyzing bacterial species, reaction pathways, and performance in crack sealing. The findings indicate that MICP can effectively fill cracks, reduce permeability, and increase the mechanical strength of construction materials, offering an eco-friendly alternative to conventional repair methods.

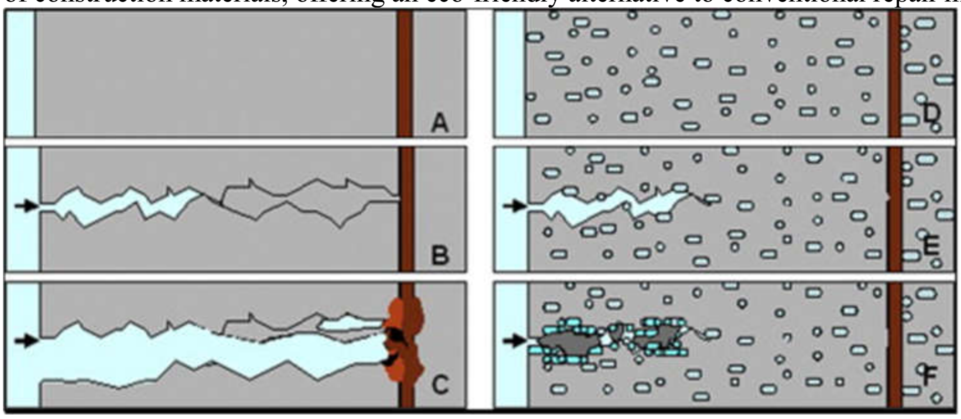


Fig:- Process of Self-Healing Concrete

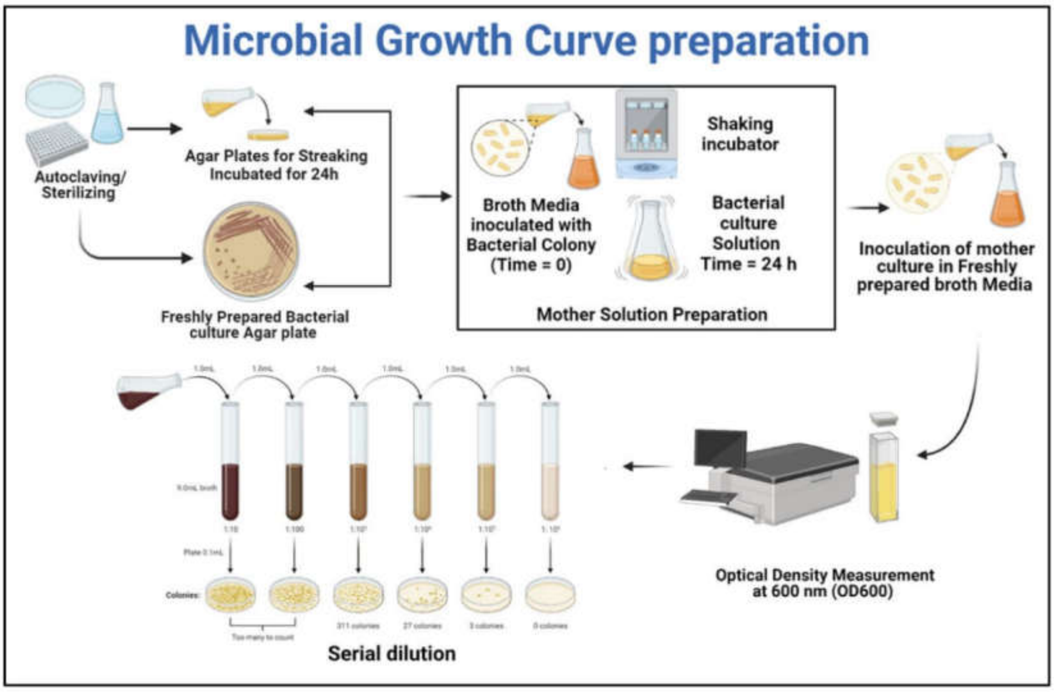


Fig:- Microbial Growth Curve Preparation

12. Self-Healing Concrete with Superabsorbent Polymers and Polypropylene Fibers *Gpta, Siddique, and Belarbi (2017)* investigated the use of superabsorbent polymers (SAP) and polypropylene fibers to enhance the self-healing capacity of concrete. Laboratory experiments were conducted by preparing concrete mixes with varying amounts of SAP and fibers, then introducing controlled cracks and monitoring healing over time under wetting conditions. The findings showed that SAP improved moisture retention for healing reactions, while fibers provided structural reinforcement, leading to faster crack sealing, increased strength, and improved durability.

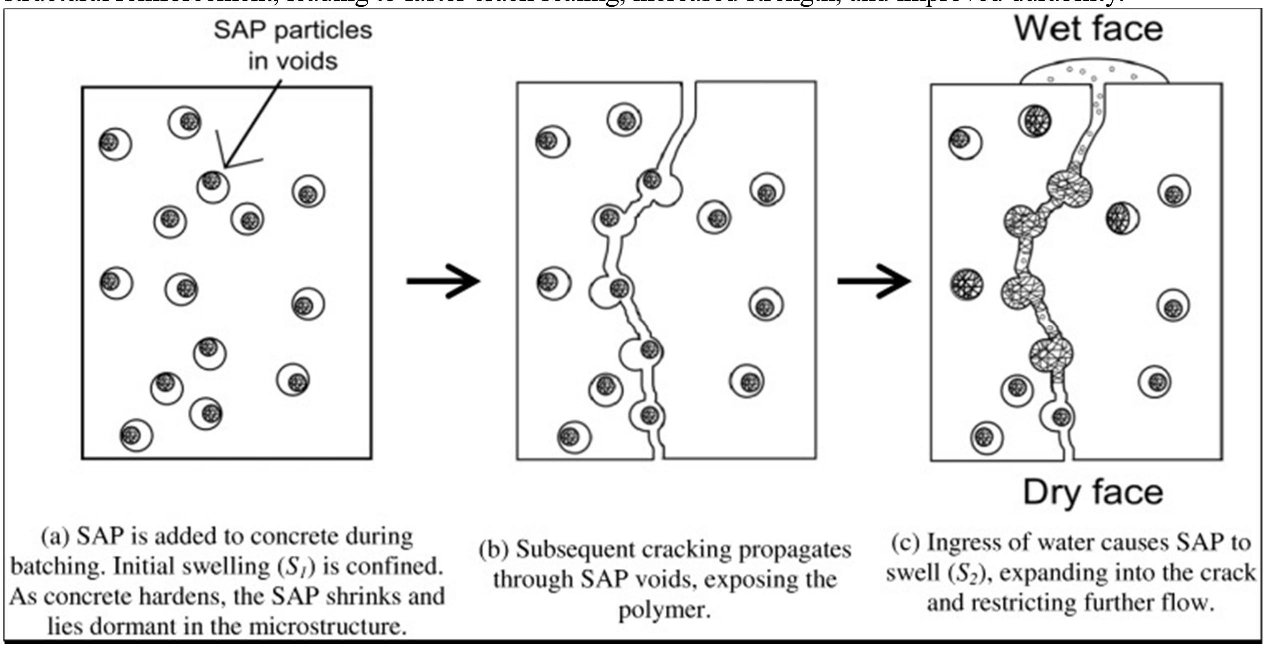


Fig:- Self-Sealing Crack Mechanism

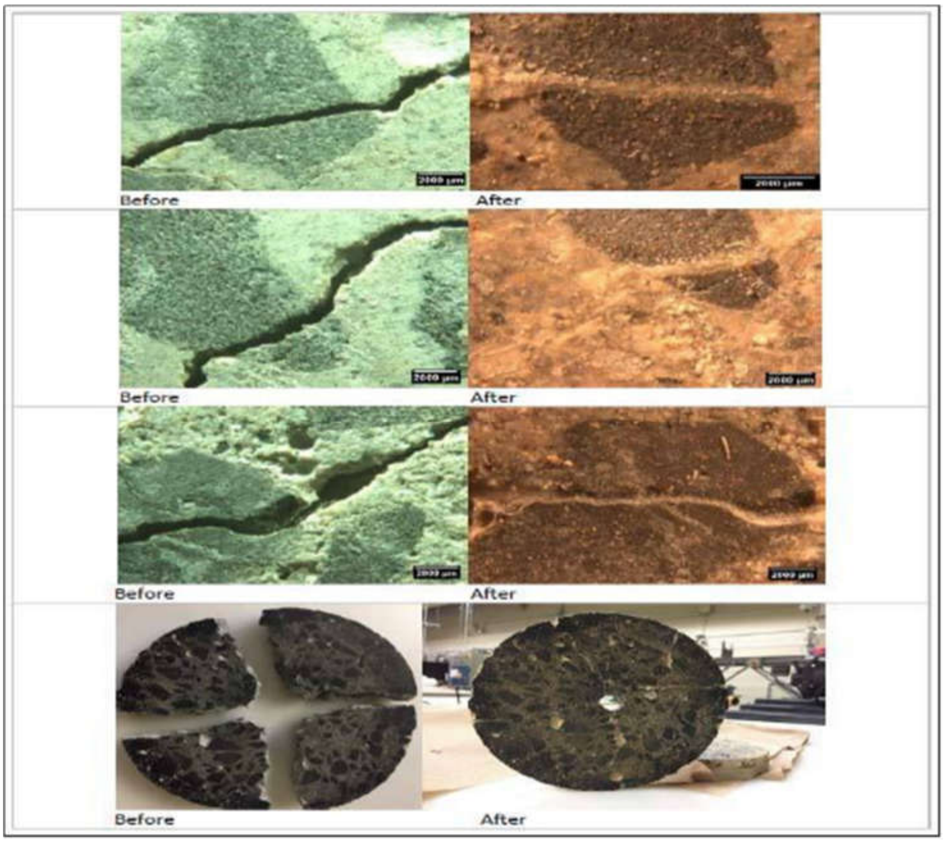


Fig:- Self-Healing Concrete Using Superabrobant

13. Enhancing Engineered Cementitious Composites with High-Volume Fly Ash — *Yang, Yang, and Li (2007)* investigated the effects of incorporating large amounts of fly ash into engineered cementitious composites (ECC) to improve mechanical properties and sustainability. Laboratory experiments were conducted by preparing ECC mixes with varying fly ash contents, then testing them for compressive strength, tensile strain capacity, and durability indicators. The findings showed that high-volume fly ash improved ECC's mechanical strength, crack control, and long-term durability while reducing the carbon footprint, making it more environmentally friendly and suitable for sustainable, long-lasting construction applications.

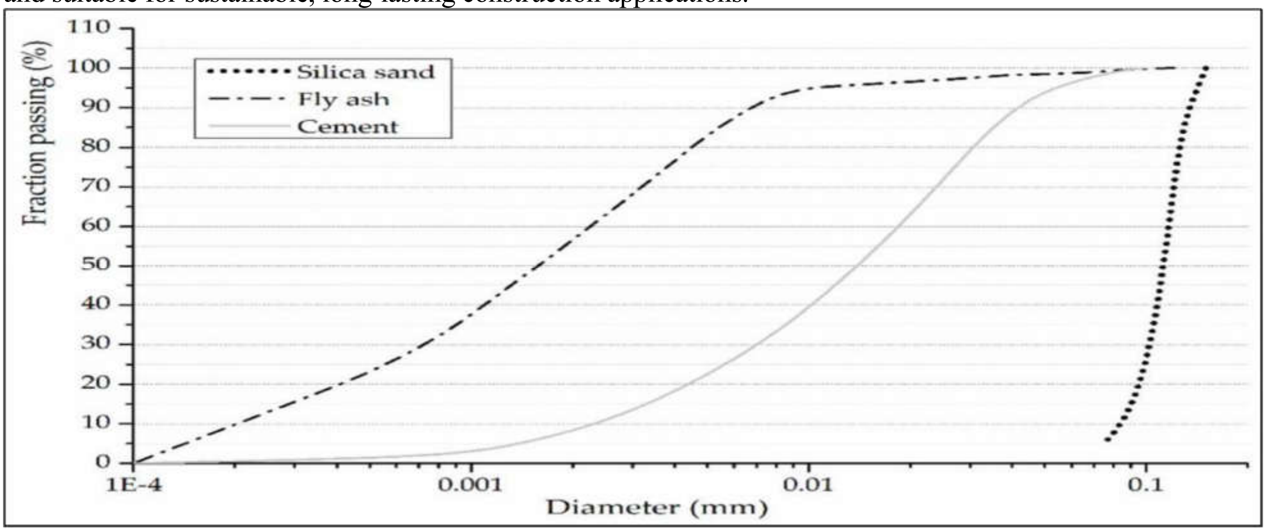


Fig:- Partical Size Distribution Curve

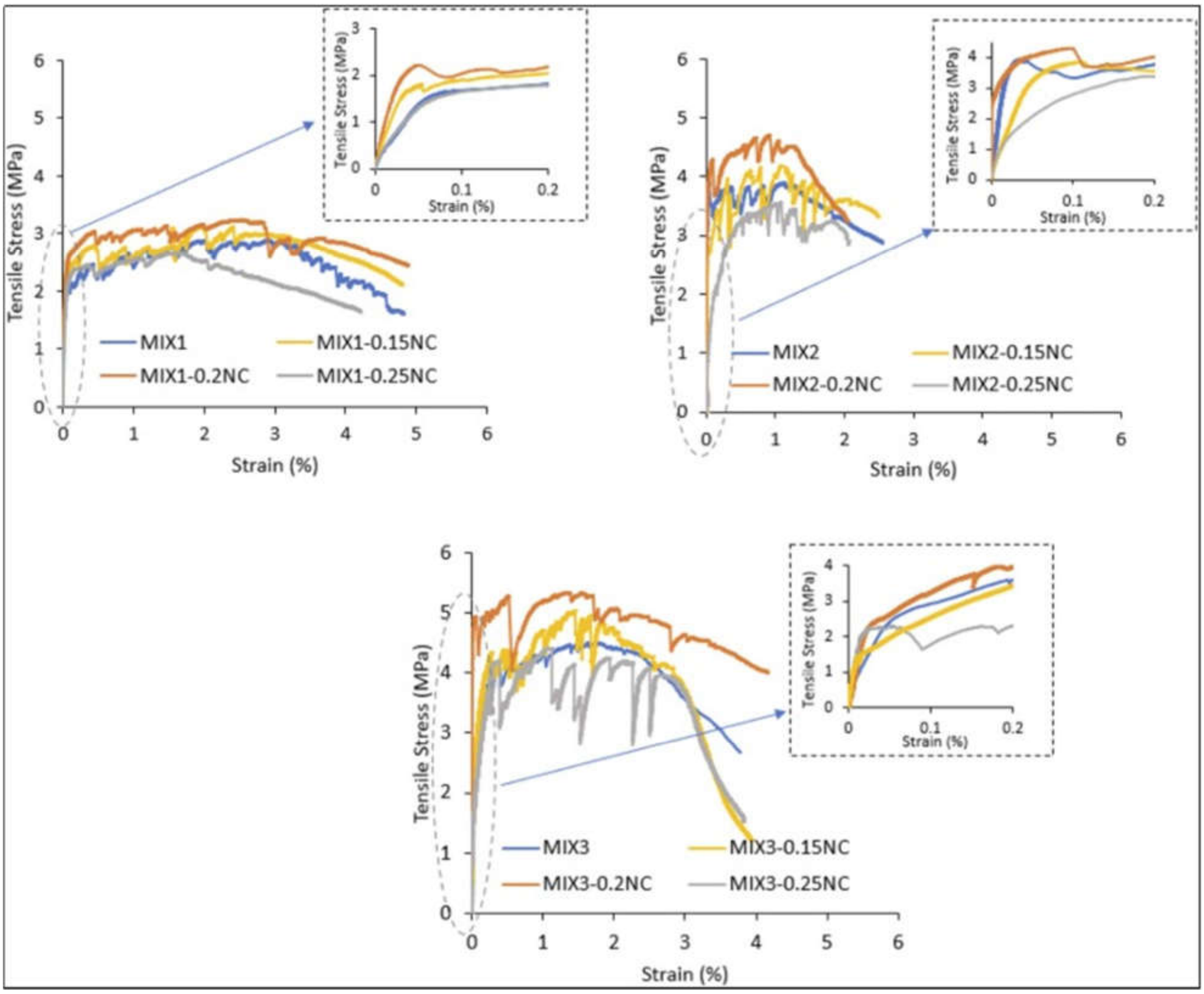


Fig: - Tensile Stress Vs Strain

14. Strong Discontinuity Embedded Approach for Modeling Crack Formation and Healing in Brittle Materials — *Zhang and Zhuang (2017)* developed a computational model to simulate the cracking and healing processes in quasi-brittle materials such as concrete. The researchers designed and implemented the SDEA within a finite element analysis environment, validated through simulations and comparisons with experimental data.
The model successfully captured the full lifecycle of crack development and healing, providing engineers with a reliable tool to optimize material design for greater strength, durability, and service life.

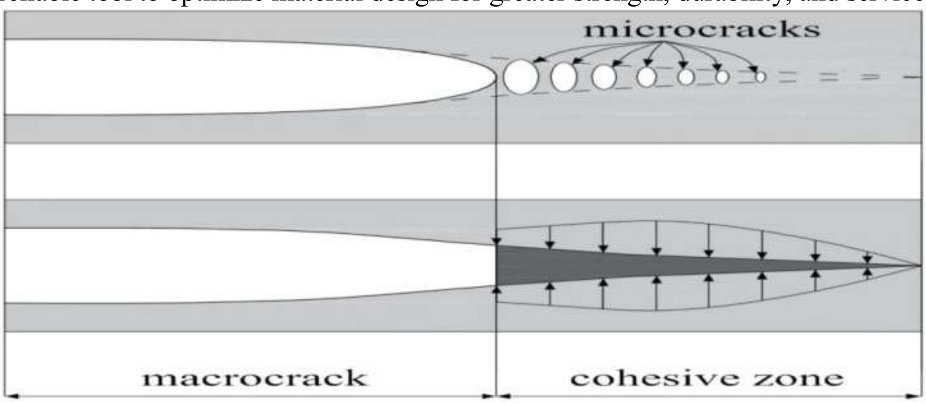


Fig: - Cohesive Zone Model

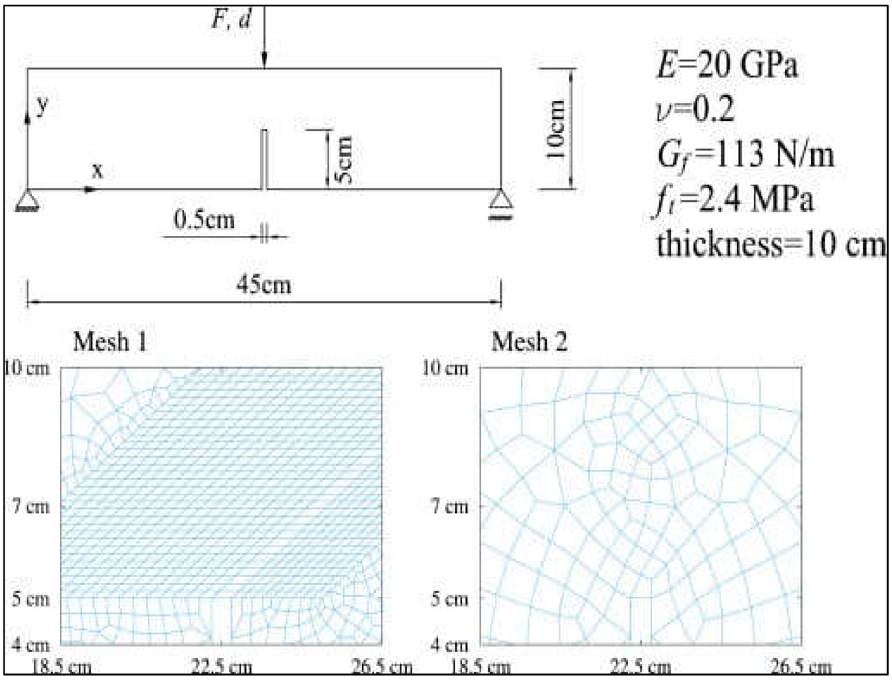


Fig:- Finite Element Analysis of Cracked Beam

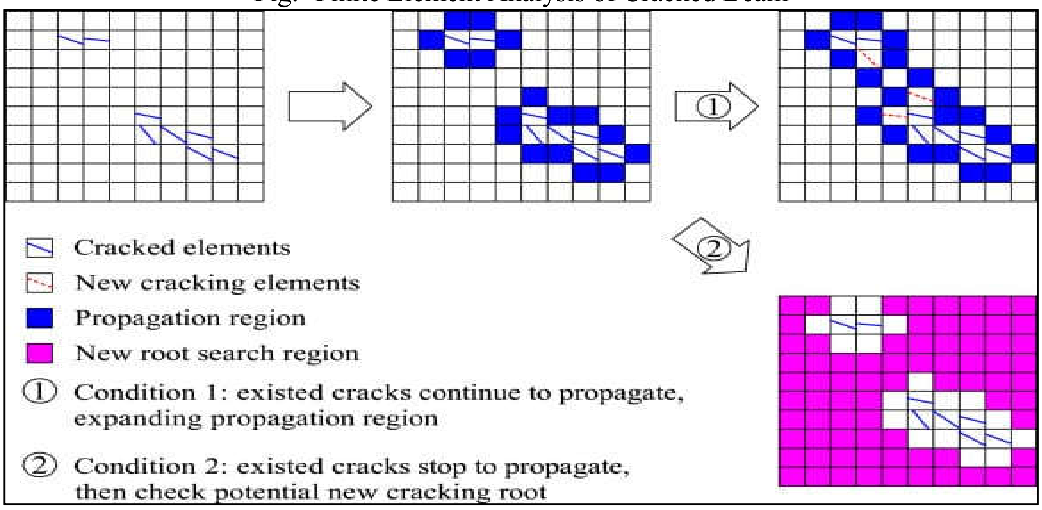


Fig:- Crack Propagation And Root Search Mechanism

15. Enhancing Self-Healing Concrete with Healing Agent-Impregnated Lightweight Aggregates — *Alghamri, Kanellopoulos, and Al-Tabbaa (2016)* investigated the use of lightweight aggregates (LWA) soaked and coated with healing materials to improve the crack-repair efficiency of self-healing concrete. Laboratory experiments were conducted by pre-soaking and coating LWA with healing agents, incorporating them into concrete mixes, and then introducing controlled cracks to monitor healing performance over time. The findings showed that healing-agent-impregnated LWA significantly improved crack sealing, maintained mechanical strength for longer periods, and enhanced the overall durability of the concrete.

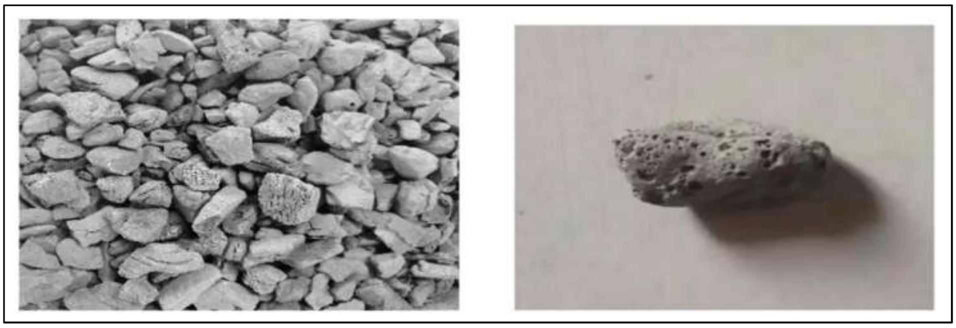


Fig:- Bentonite Lumps

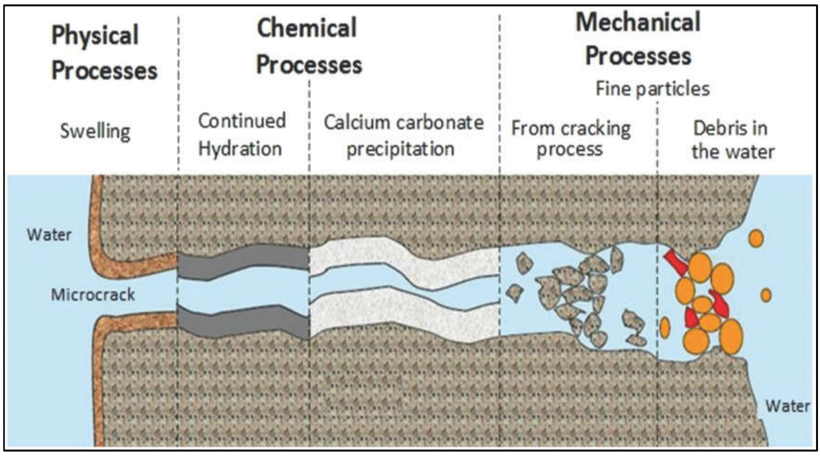
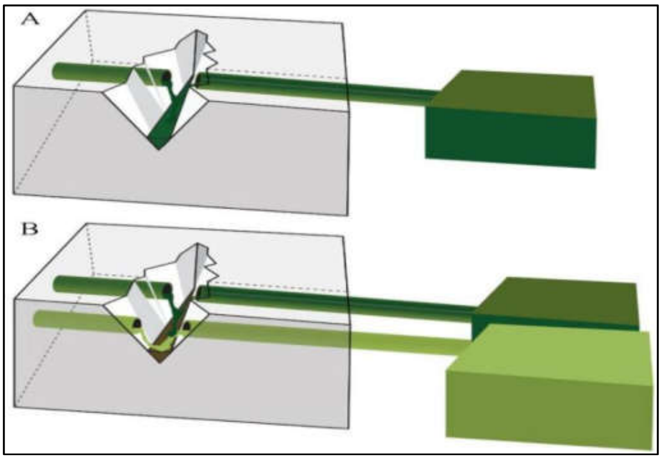


Fig:- Self-Healing Processing Concrete

16. Comparative Study of Self-Healing Agents in Concrete — *Van Tittelboom, De Belie, and Gruyaert (2012)* conducted a comparative analysis of different self-healing agents to evaluate their crack repair efficiency and impact on concrete durability. Laboratory testing was performed by introducing controlled cracks into concrete specimens containing different healing agents and then assessing crack closure, permeability reduction, and strength recovery. The findings showed that certain agents, such as specific polymers and bacterial systems, provided superior crack sealing and significantly enhanced durability compared to other materials.

Fig:- Vascular-type Self-Healing Material



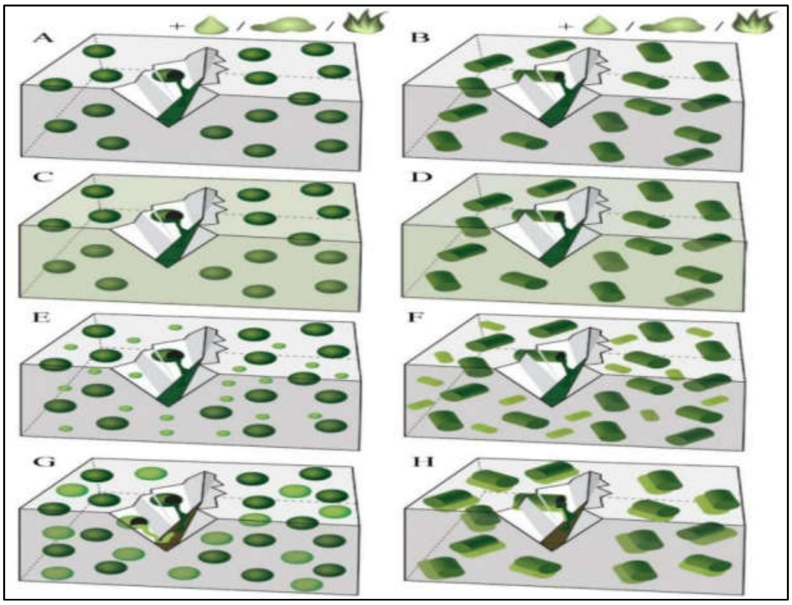


Fig:- Self-Healing Concrete

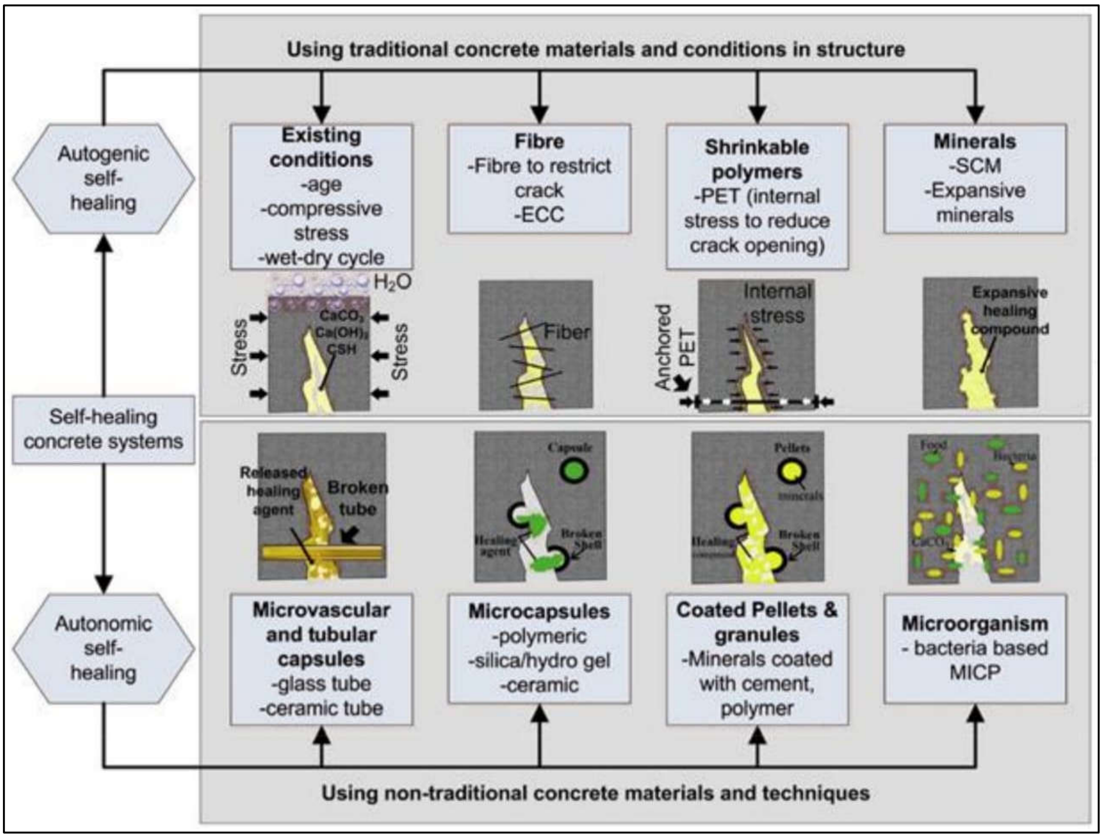


Fig:- Self-Healing Conctere Systems

17. UK Materials for Life (M4L) Project: Advancing Self-Healing Cementitious Materials for Smarter Infrastructure — *Jefferson et al. (2018)* presented findings from the UK's Materials for Life (M4L) project, which aims to develop and implement self-healing cement-based materials for long-lasting infrastructure. Field trials and laboratory experiments were conducted on infrastructure elements incorporating self-healing systems, with performance monitored under realistic environmental and loading conditions. The study found that self-healing materials effectively sealed cracks, restored structural integrity, and reduced the need for repairs,

demonstrating significant potential for improving the longevity and resilience of buildings and transport infrastructure.

Fig:- Concept Model of Trail Structure

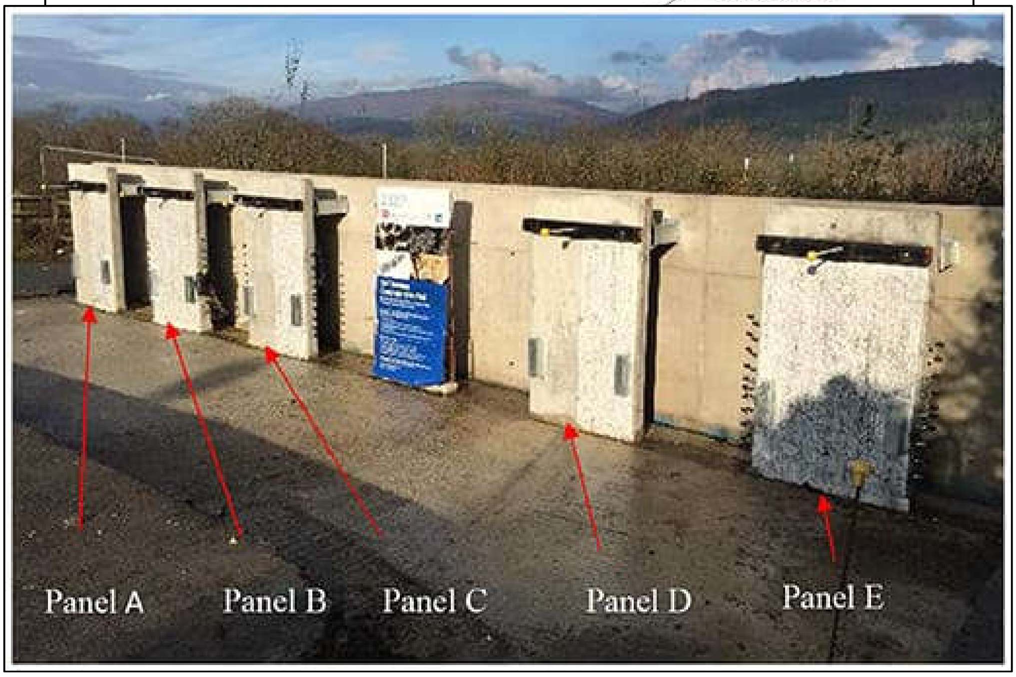


Fig:- UK's First Field Trail of Self Healing Concrete Panels

18. Bacteria-Based Self-Healing Concrete for Enhanced Durability — De Muyncks, De Belie, and Verstraete (2008)Laboratory experimentation with concrete specimens containing bacteria, Induced cracking to simulate real-world damage, assessment of healing efficiency via crack closure observation, permeability testing, and strength recovery measurements. The study demonstrated that bacterial activity successfully precipitated calcium carbonate within cracks, sealing them effectively. Concrete samples with bacteria showed improved durability, reduced permeability, and enhanced strength compared to conventional concrete, confirming the potential of bacteria-based self-healing systems for sustainable infrastructure applications.

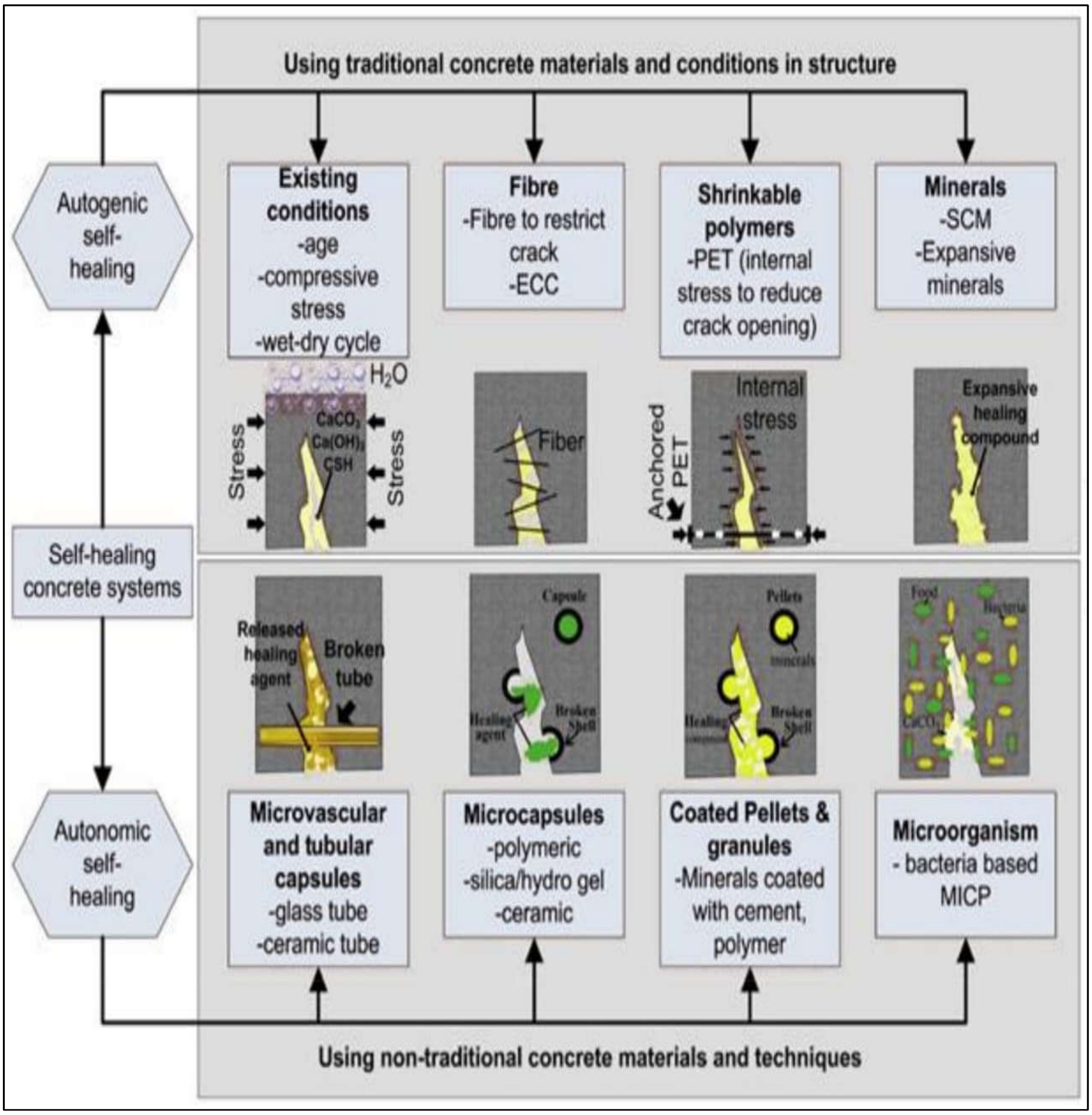


Fig:- Different Self-Healing Concrete Mechanisms

19. Crack Closure in Bacteria-Based Self-Healing Concrete — Wiktor and Jonkers (2011)Lab tests with induced cracks, monitoring healing via crack width and strength measurements.Bacteria effectively filled cracks with minerals, improving water tightness, strength, and durability, confirming self-healing potential.

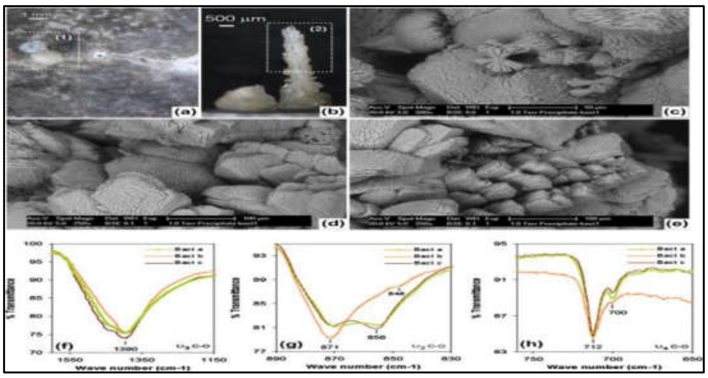


Fig:- Microscopic Bacteria Based Self-Healing Concrete

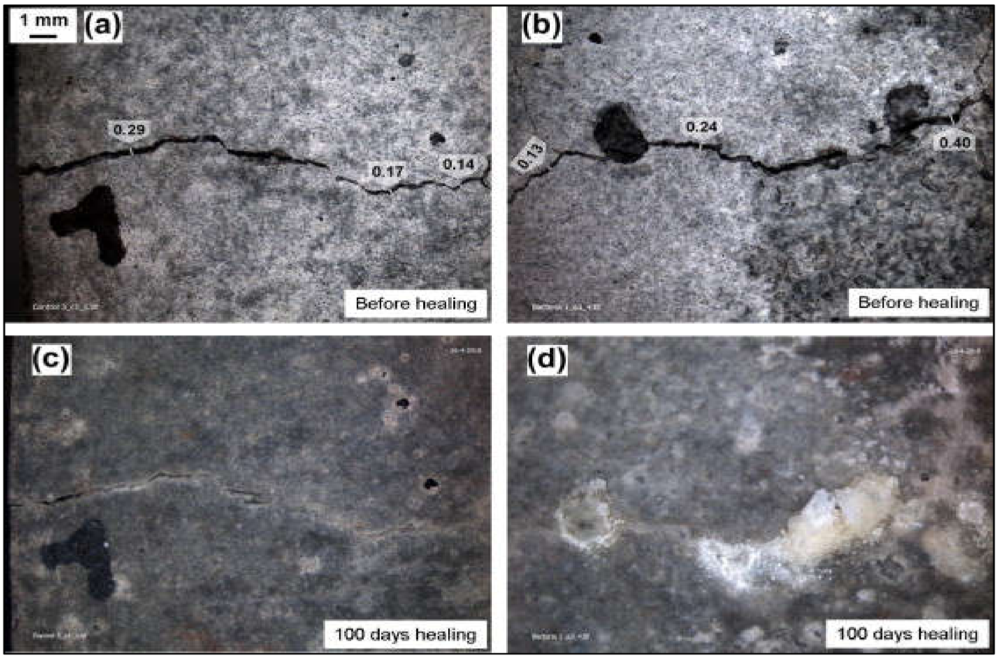


Fig:- Crack-Healing Process in Control Specimens Before Healing (a) & After 100 Days Healing (b)

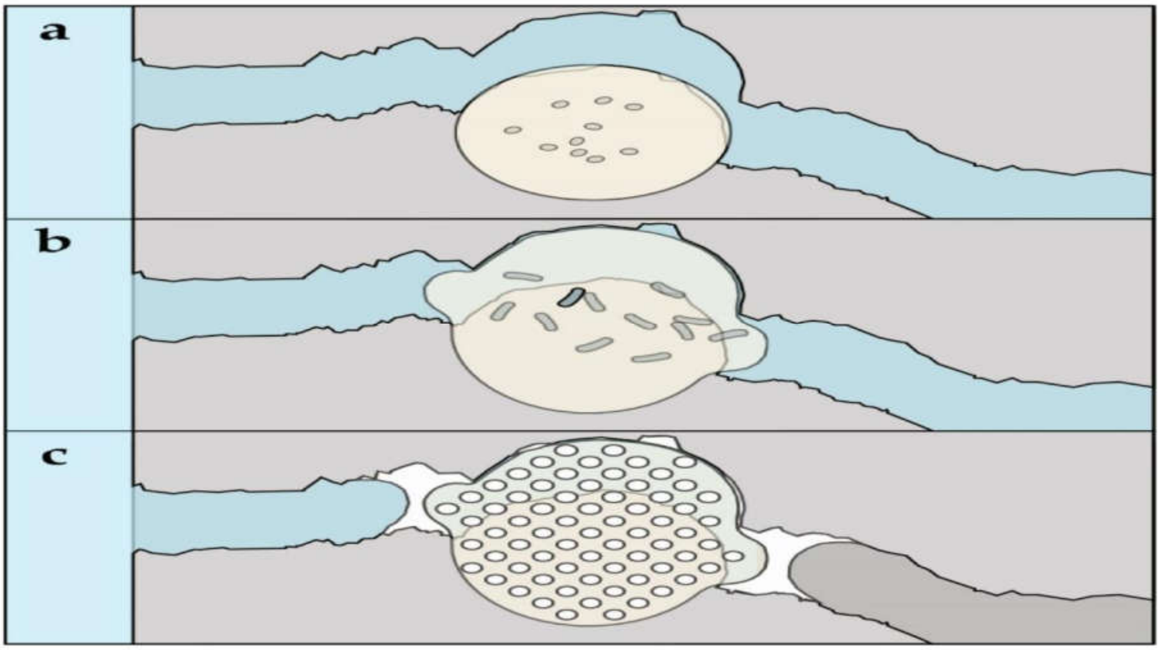


Fig:- Process of Self-Healing Concrete

20. Self-Healing in Cementitious Materials – A Review Literature review of self-healing techniques including bacterial healing, encapsulated healing agents, and chemical admixtures. The authors concluded that self-healing strategies can significantly reduce crack propagation and enhance concrete durability. Among these, bacterial healing and capsule-based approaches showed the most promise for practical applications in structural concrete.

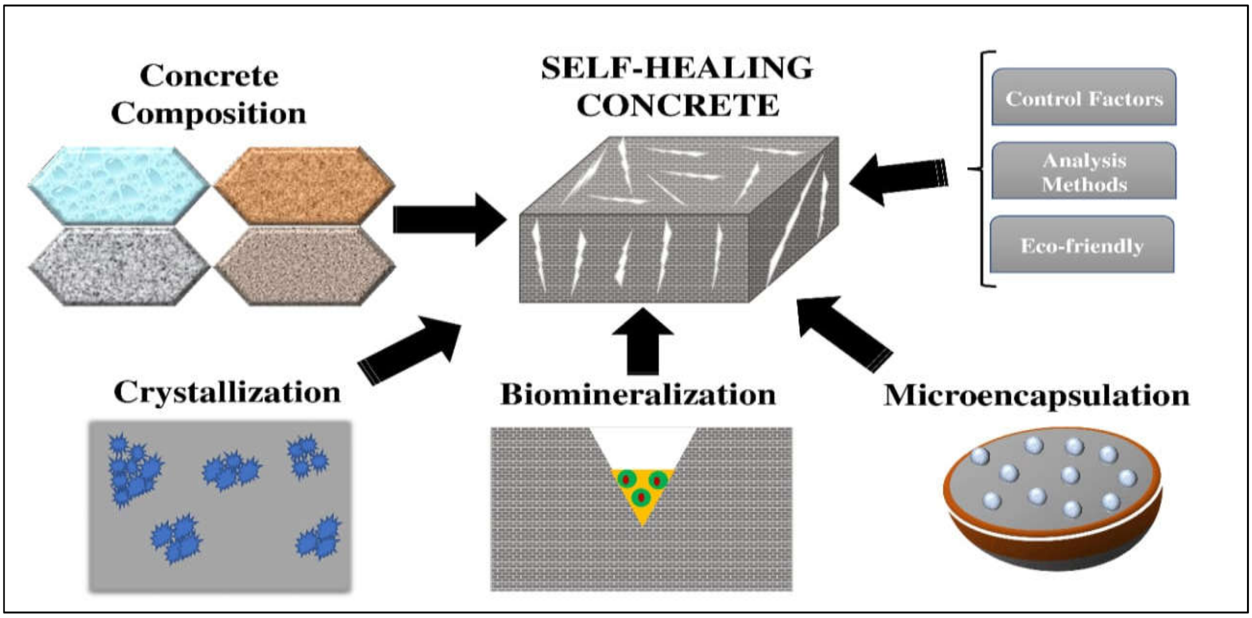


Fig:- Mechanism of Self -Healing Concrete

21. Mechanisms of Crack Healing in Concrete. Analytical study reviewing the mechanisms of crack closure through swelling, chemical reactions, and ongoing cement hydration. Each mechanism helps cracks close naturally, enhancing concrete durability, though the efficiency varies depending on crack size, concrete composition, and environmental conditions.

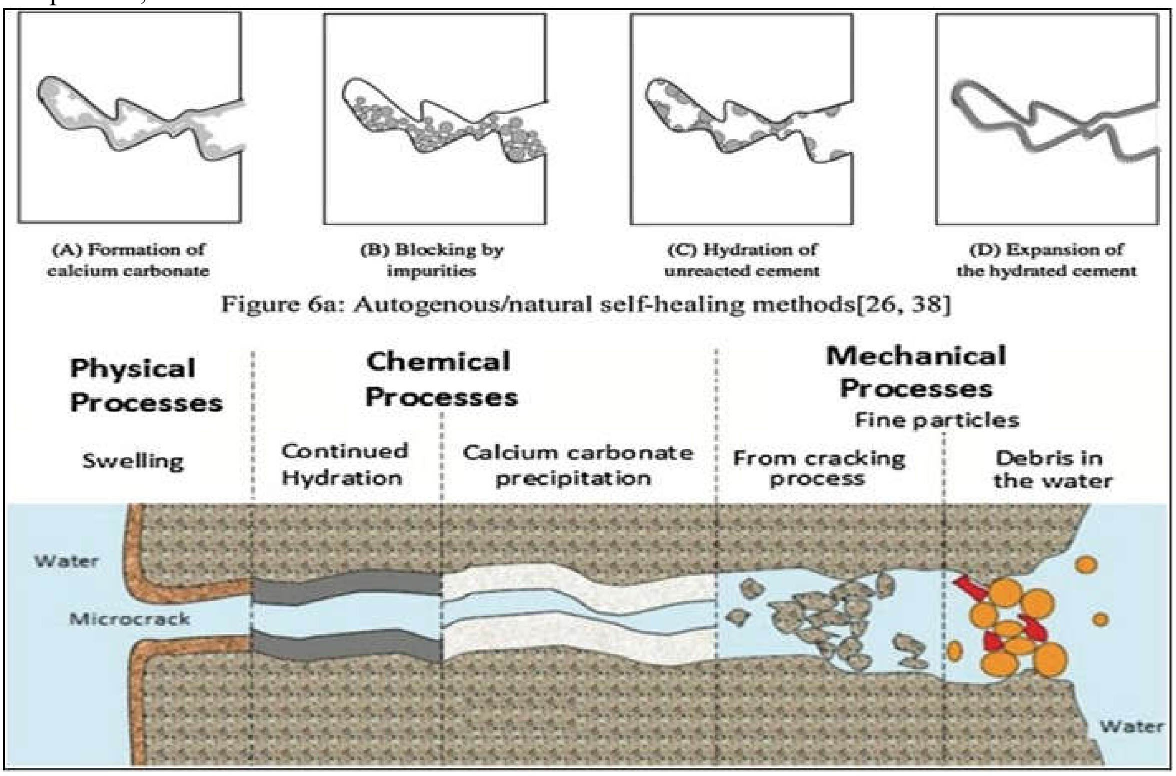


Fig:- Mechanism of Self -Healing Concrete

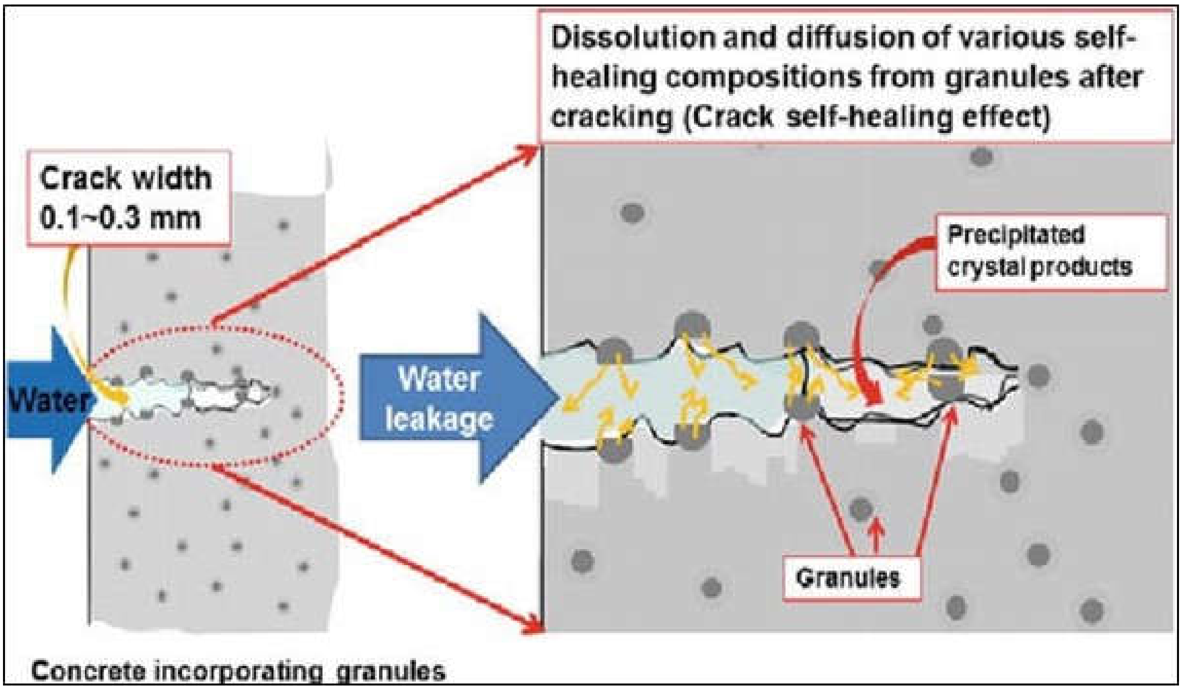


Fig:- Crack Self-Healing Effect

22. A Review on the Performance Evaluation of Autonomous Self-Healing Bacterial Concrete: Mechanisms, Strength, Durability, and Microstructural Properties. Direct Addition of bacteria along with calcium sources or nutrients. Encapsulation Techniques, where bacteria are embedded in protective carriers (e.g., lightweight aggregates, encapsulated beads). Use of lightweight aggregates and other carriers to boost bacterial survival and activation upon cracking. Encapsulation markedly outperforms direct addition for durability and mechanical recovery.

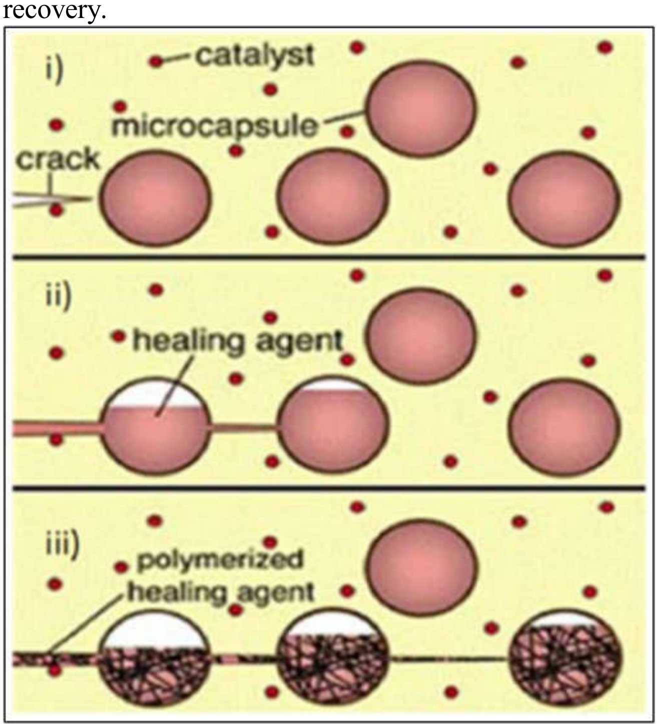


Fig:- Microcapsule Self-Healing Process

23. Self-Healing Mortars with Expansive and Crystalline Additives.
The study investigates how incorporating expansive and crystalline materials into mortar can promote autonomous crack healing and improve mechanical performance.

Experimental study on mortar samples with added expansive and crystalline compounds; observation of crack closure over time.
Surface cracks healed naturally by the formation of precipitates from the additives, improving strength and durability of the mortar.

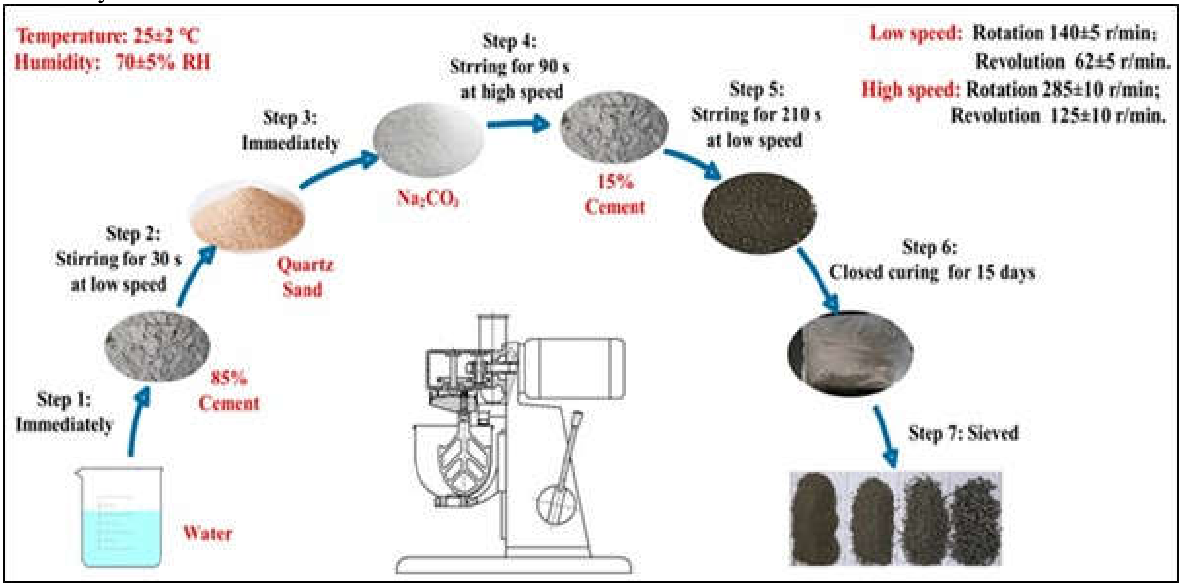


Fig:- Preparation Process Daigram

24. Environmental Assessment of Self-Healing Concrete. Life cycle assessment (LCA) comparing conventional and self-healing concrete in terms of CO_2 emissions and repair frequency. Self-healing concrete reduces overall carbon footprint, lowers maintenance needs, and extends structural life, making it a more environmentally sustainable option.

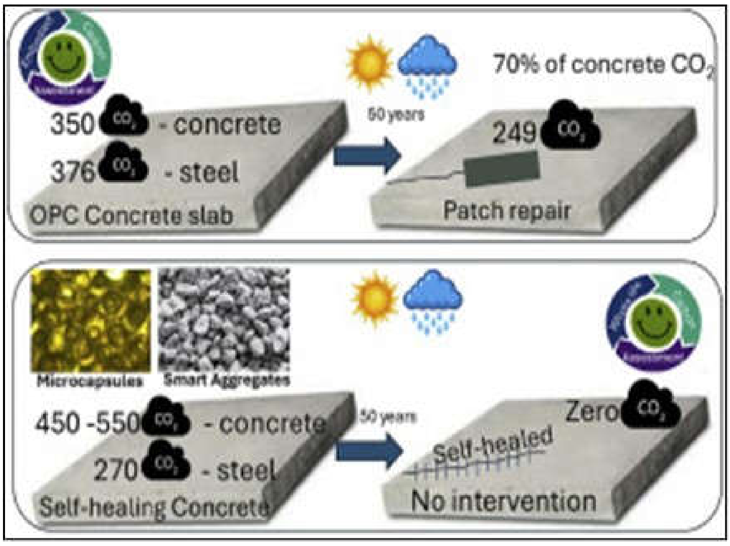
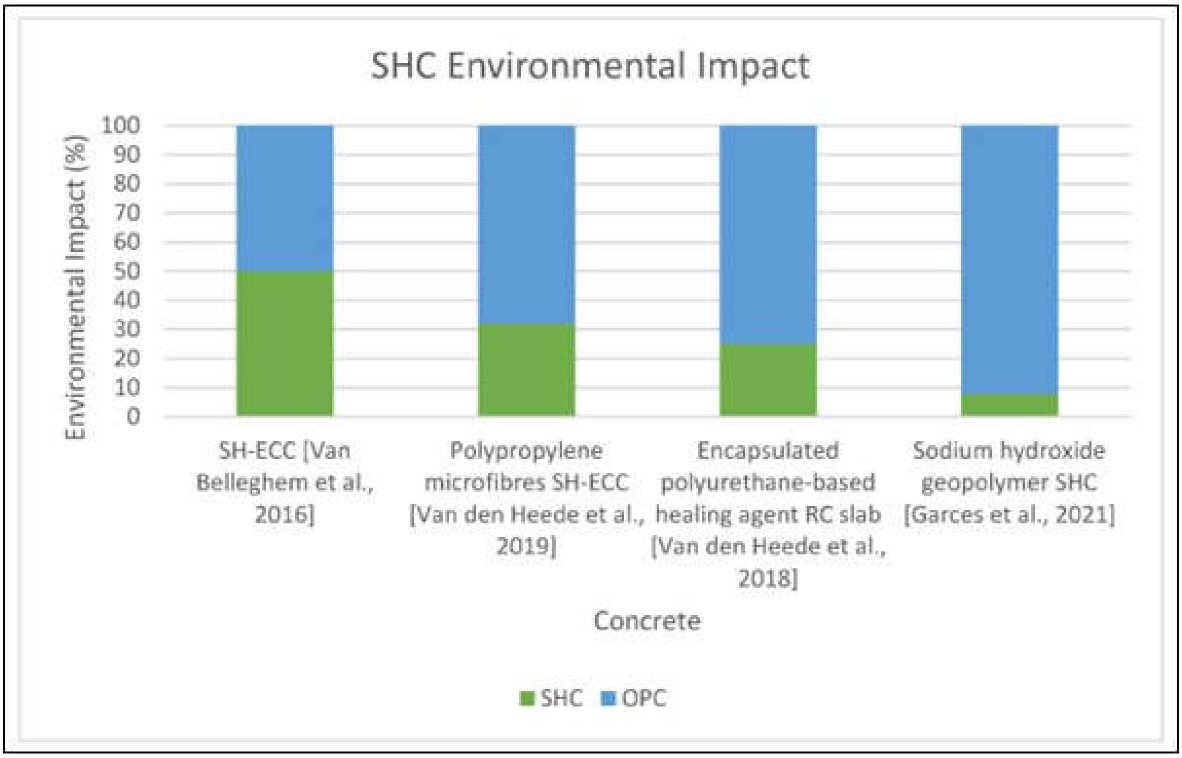


Fig:- Ordinary Portland Cement & Self-Healing Concrete With Respective CO2 Emissions



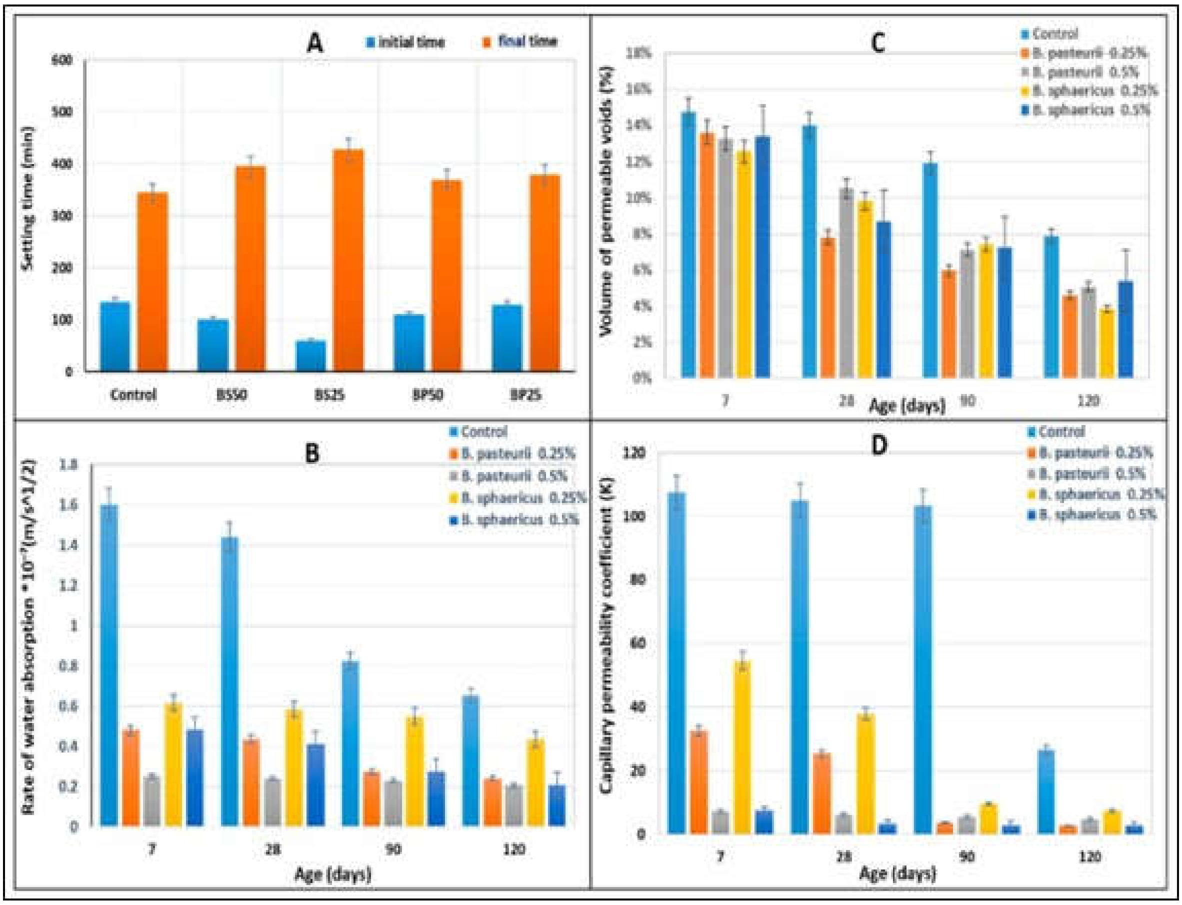
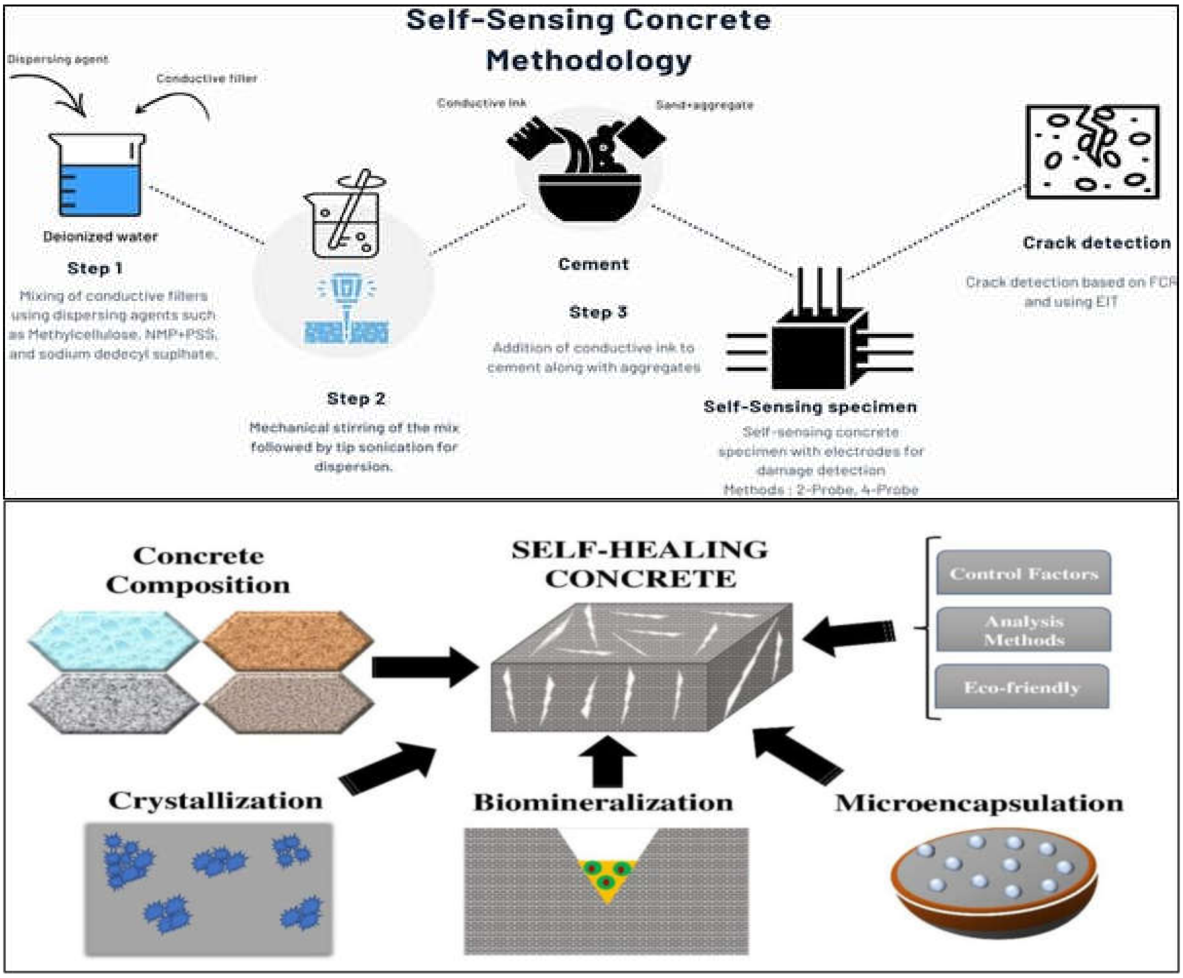


Fig: - SHC Ennvironmental Impact

25. Smart Monitoring Systems for Self-Healing Concrete. Literature review and analysis of AI- and sensor-based monitoring techniques applied to self-healing concrete structures. Smart monitoring allows for efficient tracking of crack formation and healing, optimizing the self-repair process and reducing maintenance effort.



CONCLUSION

Self-healing concrete offers a transformative solution to enhance the durability and sustainability of concrete structures by autonomously repairing cracks. Various approaches, including autogenous healing, encapsulated agents, vascular systems, and microbial methods, have demonstrated significant potential in restoring mechanical and impermeability properties. However, challenges such as high costs, limited long-term performance data, and lack of standardized evaluation methods hinder widespread implementation. Continued interdisciplinary research, field-scale testing, and the development of cost-effective and environmentally friendly healing agents are essential to advance this technology. With further innovation and validation, self-healing concrete could become a mainstream material in modern infrastructure systems.

CONCLUSION

Effective Crack Repair Mechanisms: Multiple techniques autogenous healing, capsules, vascular systems, MICP, fungi, and SAP have been experimentally validated to significantly repair cracks in concrete.
Environmental Sustainability: Self Healing Concrete lowers carbon emissions by reducing frequent repairs and using waste by product materials.

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