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A New Insight from Literature on Microbe-Assisted Self-Healing of Concrete Micro Cracks

Zeenat Khan*,[1], Majid Ali[2]
[1]*Department of Biotechnology, Capital University of Science & Technology, Islamabad, Pakistan.*
[2]*Department of Civil Engineering, Capital University of Science & Technology, Islamabad, Pakistan.*
Corresponding Author E-mail:khanzeenat2611@gmail.com, majid.ali@cust.edu.pk

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Abstract

In this modern world, concrete is still the prime construction material, and cracks are the intrinsic weakness of concrete. These cracks cause seepage of water, which leads to corrosion and thus weakens the structural strength. Many techniques are available in civil engineering to repair these cracks, but these require a high cost of implementation. At the same time, majority of these frequently adopted techniques (i.e., chemicals, resins, polymers etc.) are not environment friendly. In last two decades, bacteria (when directly or indirectly mixed in concrete) have been reported for automatic crack repair. Thus, the goal of this literature research is to provide a comprehensive review of the potential of bacteria for self-healing of concrete. The articles published in highly reputable journals in the last decade are considered. First, cracks, its causes and recommended solutions are discussed in detail. And then, philosophy involved in
concrete self-healing with focus on bacteria and its mixing techniques in concrete are elaborated. Based on this, suitable bacteria are recommended as environment friendly and cheap approach for self- healing of concrete. Finally, the adoptability of bio concrete in developing countries is debated, considering its pros and cons. Bio concrete can be used in real life structures after its in-depth investigation for global behavior.

1. Introduction

Concrete plays a vital role in construction, and cracks in it hold significant importance. A developing biological self-healing technique aims to resolve this issue of concrete cracking. Concrete suffers from physical, chemical, and biological conditions. Experimental results have shown that concrete is strong in compressive loading but weak in tension. To address this weakness in tension, steel reinforcement is introduced to counter the load when concrete fails [1]. This weakness of concrete causes cracking, which can be either micro or macro in nature. Concrete cracks result from factors like tension, freeze-thaw cycles, shrinkage, indicating diverse causes. Cracking can also occur during the hardening of concrete, ultimately leading to structural failure. Loading beyond the limit causes macro cracks, while various factors lead to micro cracks. Sometimes these cracks are noticeable, but often they are ignored [2]. Water droplets may enter concrete cracks over time, depending on their location and the situation. Water permeability enlarges cracks, leading to increased volume and corrosion of steel reinforcement in concrete. Cracks manifest in various types (from various causes) and introduce themselves as potential threats. Cracks in concrete are crucial as they jeopardize structural integrity and elicit negative responses to tensile stress.

To heal cracks, there are several ways that can be either automatic or non-automatic. Non-automatic methods require human efforts, which are not only time-consuming but also costly. Automatic methods utilize self- healing processes where a healing agent autonomously repairs concrete cracks. Self-healing can be achieved through various means, including the use of chemicals and minerals. However, these methods can have a significant impact on the environment and human life. Microorganisms are the favored choice in civil engineering for crack repair, as proposed by biotechnology [2]. Bacteria, a well-known organism for precipitating calcium carbonate, is used for sealing cracks. $CaCO3$ precipitation done by a process called bio-mineralization. It typically involves two pathways for the formation of this compound [3]. The choice of pathway depends on how bacteria are mixed into the concrete mixture. Autotrophic pathways directly add bacteria, while heterotrophic pathways encapsulate and modify bacteria for nutrients addition [4]. Ureolytic strains thrive in high pH and facultative anaerobic environments, making them resilient and preferred for their longevity. The selection of bacteria is also based on these characteristics. The suitability of bacteria for long-term use is examined by various researchers and reported in literature reviews. Assessing the extent of crack repair is crucial as concrete cracks directly impact the structural integrity. Bacteria-based concrete is one of the most suitable methods for maximizing crack repair in concrete. Optimal conditions for crack repair involve bacteria selection, concentration, survival conditions, concrete mixing, and calcium carbonate precipitation.

Bio-concrete is a promising, eco-friendly, cost-effective approach. But its adaptability is limited due to challenges, cost of implementation, and time constraints. Bio mineralization is an ancient technique, while concrete is an invention of the 19th century. Researchers aim to attain desired concrete properties through experimentation, with bio-concrete displaying great potential for self-healing micro cracks [5, 6]. Finding suitable bacteria, proper nutrients, and effective mixing methods are crucial for cost reduction and optimal outcomes. Mixing bacteria with concrete is simple in a controlled lab, but skilled labor is necessary for field applications. This presents a significant hurdle for the widespread usage of bio concrete at the industrial level. However, promising results have been observed in experiments comparing bio concrete with other chemical methods for crack repair. Since cracks directly affect the stability of structures, bio concrete is seen as a valuable solution. Success hinges on employing bacteria with crack repair traits and addressing factors to mitigate micro cracks under stress [7]. However, the challenge lies in achieving adaptability at an industrial level. Bio-concrete encounters obstacles in industry adoption, but experimentation and skill development programs can overcome these challenges.

Keeping in view the extensive usage of concrete in today's world, damage to concrete is unavoidable [1, 2]. To address this issue, it is crucial to focus on potential solutions, and among them, bio concrete emerges as the best option. Micro cracks are hair-like cracks that just begin to start. Bio concrete is primarily designed to heal these micro cracks. Because, when micro cracks will be healed, formation of macro cracks will be prevented [8]. To achieve this objective, various articles published in highly reputable journals over the past decade have been studied. At start, concrete, cracks, its types emerged from various causes are studied. Phenomenological aspects of bio concrete are explained by shedding light on healing agent's formation pathways and techniques. The preference to bio concrete is also explained on the basis of cost and environmental effects. After in depth study of bio concrete suitable bacteria are suggested by overviewing the experimental results. At last, adaptability of bio concrete is argued with focus on developing countries.

2. Cracks, its causes and available solutions

Different cracks are formed due to various causes. Multiple repair techniques exist, but employing bacteria is regarded as a superior approach for concrete repair. The presence and size of cracks greatly impact the overall structure of concrete. These cracks are a result of tensile stress during execution and external factors such as loads and stresses. Cracks expose steel to the environment and causes water penetration, reduced structural capacity, corrosion, and diminish durability. In reinforced concrete structures, cracks indicate the ingress of harmful elements. Cracks in concrete also contribute to the reduction of carbonation resistance. Water penetration through cracks subjects the concrete to freeze and thaw cycles, leading to structural deterioration. Cracks become incurable once hardened, emphasizing the need to extensively minimize and manage them during the plastic state. Despite meticulous care and controlled conditions, numerous factors can cause cracks in concrete and structures. These causes include elastic deformation occurring at material junctions within the concrete, thermal movements resulting from temperature fluctuations, shrinkage and expansion, settlement and foundation movements, segregation, roots growing near the foundation, the formation of weak zones (interfacial transition zones) at the interaction between cement and coarse aggregate, autonomous shrinkage due to low water-cement (w/c) ratio, subgrade movements before concrete hardening, creep (slow elastic deformation), and formwork movements [9]. Concrete can be categorized into pre-hardening and post-hardening states, each associated with different types of cracks (Table 1). Exploring various crack types help to understand their formation mechanisms, as they can result in structural damage and failure. The solutions for repairing these cracks are generally cost-effective but require significant human effort.

Bacteria surpasses other techniques by addressing strength reduction caused by water-filled cracks and pores in concrete. There are several methods available to repair these cracks (Table 1). However, these methods are expensive, labor-intensive, and environmental unfriendly. Biotechnology, when integrated with other domains, offers cost-effective solutions for diverse issues, such as concrete crack repair. While concrete and its cracks are typically linked to civil engineering, biotechnological approaches provide cost-effective and eco-friendly solutions. Research and ancient techniques highlight bacteria's role in forming calcium carbonate precipitates to seal concrete cracks [10]. Bio-mineralization is a self-healing process where bacteria catalyze the reaction, forming calcium carbonate in concrete. The pathways for calcium carbonate formation vary based on bacteria, their nutritional needs, and crack locations. The exothermic energy during concrete formation and freeze-thaw cycles increase the likelihood of crack formation in regular concrete. Bacteria can survive harsh conditions and aid in maintaining favorable conditions to prevent concrete cracking. Repairing these cracks using alternative techniques can be costly and have adverse environmental impacts.

Table 1. Types of Cracks and their solutions [1, 3, 9]

Sr. No.	Type of Cracks.	Reasons.	Solutions.
1	Offset Cracking	When few parts in concrete are broken due to difference in heights offset crack occurs.	Resurfacing, crack sealing, reconstruction.
2	D-Cracking	Inability of concrete to sustain during freeze and thaw condition causes D-Cracking.	Drainage, surface sealing, epoxy resins.
3	Plastic Shrinkage	Occurs in a very small length but runs to the mid of concrete and spread in all parts.	Water curing, fogging, plastic sheets, joint placement.
4	Spalling	Moves along the rebar and have higher depression than cracks and scaling.	Expansion joints, protective coating, drainage.
5	Hairline Cracking	Occurs because of variation in temperature and is very thin and deep.	Sealants, crack injections, joint installation.
6	Map Cracking	Extends in 1200 angle from surface and is fine and shallow.	Chemicals, epoxy, sealants.
7	Scaling	The disclosure of outer aggregates occurs because of the loss of outer surface.	Sealants, chemicals, resins.
8	Pop-Outs	Because of low humidity aggregates with high pores absorbs water and these type of cracks occurs.	Non-reactive aggregates, control moisture, adequate curing.

3. Self-healing of concrete

Self-healing is a great way to fix cracks, with two types: passive and active methods [11, 12]. Passive cracks are visible on the concrete surface and are typically repaired by human intervention. They mainly address exterior cracks and sometimes interior cracks connected to the exterior. Passive treatments include coatings, sealers, and concrete chipping to repair cracks with chemicals or epoxy resins. These methods are often expensive and not environmental friendly. On the other hand, active treatment is a method of addressing cracks as soon as they appear. It can address both interior and exterior cracks. Active treatment options for crack repair include polymers, auxiliary cementing materials, and natural or bacterial self-healing methods. Chemical-based active treatments are not only costly but also harmful to the environment. Therefore, it is recommended to utilize biological self-healing techniques. Self-healing techniques do not require human intervention and involve the use of cementitious materials. These methods boost structural strength, lifespan, and prevent corrosion, minimizing crack occurrence and enhancing structural integrity. A strong healing material is essential for effective self-healing crack repair, capable of enduring concrete's mechanical stress [2]. The proposed strategies aim to overcome the limitations of other techniques.

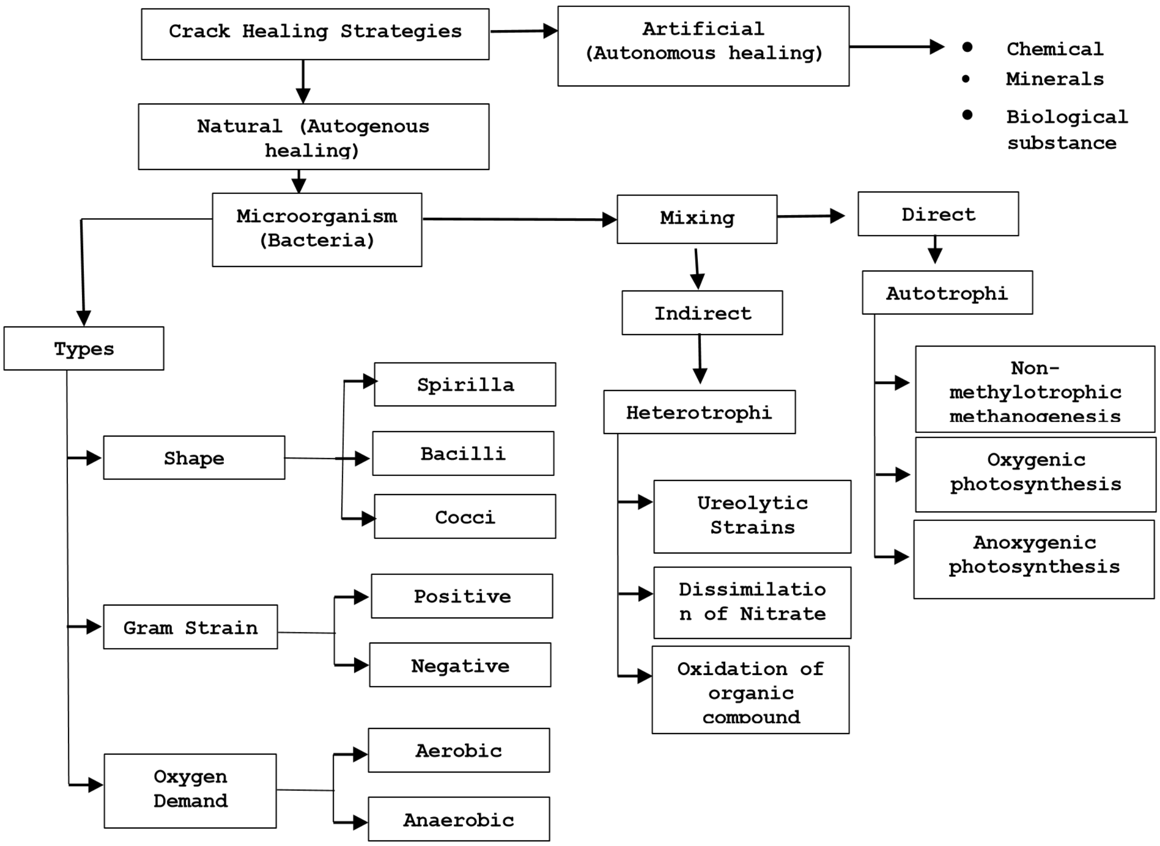

Figure 1. Crack healing strategies as depicted from [10, 11, 13,18]

Two strategies commonly used for self-healing in concrete are autonomous healing (artificial method) and autogenous healing (natural method). Autonomous healing repairs concrete cracks by adding external materials such as chemicals, minerals, or biological substances. Dispersion of these mixtures in different parts of the concrete leads to improve results. The healing agent activates only the necessary substances for healing, minimizing their usage. Limited quantities are used to prevent any impact on the mechanical properties of cement. For self-healing, bacterial growth in concrete requires prerequisites and chemicals, which can compromise its mechanical properties (25 g) [11]. Autogenous healing is a natural process in concrete where cracks can partially or completely close over time. The process of autogenous healing allows for the recovery of physical, mechanical properties, and initial durability in concrete. Autogenous healing involves crack carbonation, converting Ca(OH)2 into calcium carbonate to seal cracks, and unhydrated material hydration. This technique can repair cracks with widths ranging from 0.2 mm to 0.3 mm. Both strategies exhibit high efficiency in terms of the percentage of recovery achieved. The choice of mixing method (direct or indirect) depends on the bacteria's nature and their ability to precipitate calcium carbonate.

Table 2. Pathways for calcium carbonate precipitation, [19-23]

Pathways of calcium carbonate precipitation						
Types	Autotrophic			Heterotrophic		
Methodology	nonmethylo-trophic methano-genesis	Oxygenic Photosynthesis	anoxygenic photosynthesis	Ureolytic Strains (MICP pathway)	Dissimilation of Nitrate	Oxidation of organic compounds
Nutrients	Organic matter	Organic matter	Organic matter	Ammonia	Nitrogen & Carbonic acid	Organic matter
Ions formation	Nil	Nil	Nil	CO32-	3HCO3- & 2CO32-	5Ca (OH)2
pH level	6.5 - 8.5	7.0 - 9.0	6.5 - 8.5	7.0 - 9.5	7.0 - 8.5	6.5 - 8.5
Oxygen level	Zero	High	Zero	Moderate	Zero	Moderate
Chemical Compounds	Methanogens	Organic compounds	Depends on the type of bacteria used.	Urea	Formic Acid	Calcium Lactate
Examples	Methanobacterium specie.	Cynobacterium genus	Halobacterium and Heliobacterium species	Bacillus Sphaericus, Bacillus pasteurii, and Bacillus subtilis	Denitobacilus, Thiobacilus, Alcaligenes, Pseudomonas, Spirilium, Achromobacteri, and Microoccus species	Bacillus pseudofirmus, Bacillus subtilis, Bacillus cohnii, Bacillus alkalinitrilicus, Bacillus thuringiensis, and Bacillus halodurans
Preferable	Less than other two	Preferred due to high pH.	Less as compare to oxygenic	Preferred due to high pH. and nutrients	Less as compare to urea	Less than other two

3.1. Bacteria and its mixing techniques in concrete

Incorporating microorganisms into cement-based materials poses a significant challenge in construction research and development. Introducing bacteria into concrete enables the unique self-healing method of calcite precipitation to occur. Bacteria are defined as single-celled organisms and are classified based on their characteristics, mainly into three categories (Figure 1). Through bio mineralization, bacteria can decompose calcium and urea, generating calcium carbonate and enabling concrete self-healing. Several studies have shown that cracks with widths up to 0.97mm can be repaired using bacterial self-healing techniques [11]. This chemical reaction occurs in the presence of catalysts, which can be either chemical or biological substances. The catalyst plays a crucial role in the formation of the crack filling material. Bacterial catalysts are essential in the active chemical reaction that forms calcium carbonate, acting as crack filling material. Historical research confirms calcium carbonate's efficacy for stone preservation and its positive influence on concrete. The selection of the bacterial catalyst is crucial in determining the amount of calcium carbonate formed.

Direct mixing is the easiest way, while indirect mixing is a slightly more complex method. In direct mixing, bacterial cells are directly added to the water. Bacteria strains capable of thriving in highly alkaline environments with limited nutrients are identified when added to cement [13]. Encapsulating bacterial concrete eliminates the need for water regulation, making it a more effective method for self-healing. Indirect mixing is a versatile technique for various purposes, including three general methods of immobilization: (1) pellets and flakes, (2) microencapsulation in gels, and (3) encapsulation in porous solids [14]. Encapsulating calcium lactate and yeast extracts in quantities less than 6% and 0.1% of aggregate mass aids self-healing [15, 16]. Bacteria are vital for calcium carbonate precipitation, necessary for crack repair in concrete when mixed under suitable conditions [17]. Bio mineralization is the phenomenon of converting organic matter into inorganic matter with the help of living organisms. This phenomenon aids the civil engineering department in addressing various construction issues, including crack repair through calcite precipitation. The precipitation of calcium carbonate results in the formation of three minerals: aragonite, vaterite, and calcite. However, research has shown that calcite is preferred by bacteria for self-healing due to its thermodynamic stability. For bacteria-induced CaCO3 precipitation in crack healing, two main types of methods, with various techniques, are employed. And MICP (Ureolytic strains) pathway is considered to be best for CaCO3 precipitation.

Table 3. Literature Review on most commonly used Bacillus specie of bacteria in concrete

Sr. No.	Bacteria	Mechanical Test	Monitoring technique	Caco3 precipitation technique	Aerobic / anaerobic	Nutrients	Result	Ref.
1	Bacillus pasteurii Bacillus sphaericus	Compressive and Flexural	SEM, EDAX, and DTA	Ureolytic Hydrolysis	Aerobic facultative anaerobic	Phosphate, Ammonia, Acetate	At optimum conditions were 0.25% of B. sphaericus or 0.50% of B. pasteurii with 0.125% of calcium lactate, showed flexural strength restoration up to 2.3 and 2.6 folds	[27]
2	Bacillus subtilis	Compressive strength and Water absobtion	XRD, FTIR, SEM, and EDX)	Urea Hydrolysis	Aerobic or facultatively anaerobic.	Amino acids (glutamine & glutamate)	The bio concrete with 109 cells/mL (BC-9) of Bacillus subtilis shows a 25.9% increase in compressive strength	[21]
3	B.cohnii B.halodurans B. pseudofirmus	Non	ESEM	Urea Hydrolysis	Aerobic	KH, P0, /Na2HP04 buffer.PH 7-2.15 mMammonium sulphate, Sodium acetate	bacteria incorporated in high numbers (109 cm-3) do not affect concrete strength, that a substantial number of added bacteria remain viable	[28]
4	Bacillus. Cereus	water and chloride permeabilit y	SEM	Urea Hydrolysis	Obligate Aerobes	Glucose, Malate, Simple sugars, Dipotassium phosphate, Citric acid	The water absorption and chloride permeability of the specimens treated in this way were 12% and 10.9% lower than those of the reference specimens, respectively	[22]
5	Bacillus safensis Bacillus pumilus	Compressive test and UPV	SEM, XRD and TG analysis	Urea Hydrolysis	Facultatively anaerobic	Calcium lactate and yeast extract	47 % healing and effectivenes s by UPV test and 86 % strength recovery index endorse the viability of bacterial strains in alkaline cementitious environment	[20]

3.2. Suitable bacteria for concrete self-healing and its role in concrete strength improvement

Factors like scale-up, cost-effectiveness, and practicality need to be considered. To ensure the suitability of bacteria-based self-healing techniques for real-world applications. The suitability of bacteria depends on their nutritional requirements, food-making nature, and oxygen demand, impacting strength changes. Different bacteria can boost calcium carbonate precipitation. The focus is on selecting bacteria with positive impacts and minimal harm to humans. Many bacterial strains have been studied and employed for concrete self-healing. Bacillus specie (gram positive, rod shape, heterotrophic) excel with eco-friendliness, soil availability, rapid healing, urease production, and resistance, enhancing effectiveness [18]. Bacillus pasteurii is highly suitable among Bacillus specie, with a 30% calcium carbonate formation rate. Bacillus safensis is unsuitable, showing minimal calcium carbonate production. It has negligible impact on concrete strength based on multiple studies conducted over 28 days [24]. Various Bacillus subtypes are used for concrete self-healing, based on their nutritional needs and survival conditions (Table 3). They are ranked according to their percentage of calcium carbonate production and strength improvement.

Bacteria can enhance the strength of a structure by directly improving the concrete composition. Experimental results have shown that bacteria outperform other strategies for repairing micro cracks. Bacteria itself does not directly heal the cracks. Bacteria plays a crucial role in the chemical reaction that leads to the formation of calcium carbonate. And cracks are filled by calcium carbonate. The strength of the concrete depends on the bacteria because the precipitation of $CaCO_3$ relies on bacterial activity. The crack filling is determined by the bacteria concentration (CFU) and affects the percentage of concrete strength improvement. Suitability is assessed by considering the duration of healing after activating the healing agent [25, 26]. Literature highlights that concrete cracks can be filled, enhancing strength, through $CaCO_3$ precipitation facilitated by diverse bacterial species. Optimal improvement occurs when specific bacterial species are present in the right concentration and meet their nutritional needs. Monitoring the behavior of concrete and the response of bacteria are two key aspects to consider. Both will be monitored according to their properties to achieve the desired results. This study analyzes literature (Table 3) on bacteria-mixed concrete experiments, emphasizing bacteria type, strength tests, and monitoring techniques. The results obtained from mixing bacteria in concrete under various conditions [12]. Suitability and strength improvement depend on selecting bacteria with appropriate requirements and considering their environmental effects. Bacillus species are favorable for high calcite precipitation percentage via the MICP (Ureolytic strains) pathway. Most common techniques for monitoring results include SEM, EDAX, and DTA.

4. Adaptability of bio concrete in developing countries

Bio concrete is the fastest healing technique. While holding potential benefits for developed and underdeveloped nations, widespread usage of bacteria-mixed concrete remains experimental and unobserved [29]. Bio-concrete has the advantage of reactivating bacteria automatically when cracks appear, eliminating the need for human intervention. Moreover, it generates less waste during the repair process and requires skilled labor. It can also cause damage to human life if not handled carefully. Developing countries face limitations in adopting bio-concrete. Due to factors like high cost, limited resources, and specialized skills for handling living organism. Although environmental friendly, bacteria are used in bio-concrete. They can pose health risks if mishandled, due to their potential of causing diseases [30, 31]. Producing bio-concrete in developing countries can be hindered by skill requirements, limited bacteria availability, and higher costs relative to traditional concrete. Therefore, bio-concrete is not widely adopted in developing countries.

Research, experiments, skill development, resource availability, and adequate equipment are vital for potential adoption of bio-concrete in developing countries. Bio-concrete has been implemented on a limited scale in various research and experimental projects. While it has shown promising results, widespread implementation on a large scale is still in the early stages and not yet in common practice. It has been assumed that living in bio-concrete may not be safe from a physiological perspective. If bacteria are manually mixed with the concrete, despite its environmental benefits [32]. This ancient technique has gained recent popularity in collaboration with civil engineering to preserve concrete and prevent cracks. Insufficient laborers' awareness about handling living organisms hampers the wide adoption of bio-concrete in the industrial sector. Suitable bacteria are available freely, but manual mixing poses health hazards due to the lack of awareness. Raising awareness, conducting research, and skill development can enhance adaptability, if cost is not a major concern. However, cost remains a significant obstacle until research is completed, requiring sufficient funding for conducting research. Once the research is being completed cost will not remain an issue. Keeping in view the cost of repairing cracks with other technique, the implementation cost of bio-concrete is avoidable. Bio-concrete's global potential for self-healing is limited to research in developed countries; challenges in cost, resources, skills, and health risks must be addressed for adoption in developing nations.

Table 4. Merits and Demerits of Bio concrete [33]

Merits of Bio concrete.	Demerits of Bio concrete.
Compressive strength and stiffness increases to a significant level.	Cost is 7-28% higher than normal concrete but it can reduce the repairing cost in future.
Towards freeze and thaw reactions a good resistance in provided by chemical reactions of bacteria.	Bacteria can cause damage to human health so it should not be used near human life.
Amount of carbonation is directly proportional to the decrease in permeability and porosity	No standards have been made yet for bacterial concrete and suitability changes according to type of bacteria and its applications.

5. Conclusions

This review paper explores the potential of bacteria for CaCO3 precipitation in concrete. By focusing on articles published in highly reputable journals in last one decade. The current effort is to compose all published information related to bacterial specie used in self-healing of concrete cracks. Following conclusions are drawn from the conducted study:

- Concrete is the backbone of construction, but the major challenge lies in the minimization of cracks. Cracks are fractures that result from various causes and take different forms, making them inevitable. Numerous techniques, including self-healing methods, have been developed to address these cracks, achieving some success. However, these techniques often have detrimental environmental impacts and require significant financial investment. On the other hand, the utilization of bacteria as a crack repair technique offers a superior solution compared to other methods.
- Self-healing of concrete is an environment friendly technique. This technique automatically repairs the cracks without human intervention. This self-healing process can occur actively or passively. Active healing by bacteria is considered superior to others. It allows the precipitation of calcium carbonate following different pathways, which seals the cracks.
    - Bacteria is considered to be environment friendly unicellular organism. The most environmental friendly bacteria from Bacillus specie (i.e. B. Pasteurii) is suggested to be suitable for calcite precipitation if mixed with concrete indirectly via encapsulation. This bacteria can achieve maximum percentage of crack repairing by bio mineralization process following MICP pathway for CaCO3 precipitation.
    - Bacteria can improve concrete strength up to a high number. To evaluate the results, numerous tests and monitoring techniques are available with respect to area of interest. SEM, EDAX, and DTA techniques are commonly used techniques to evaluate the results of bio concrete self-healing.
- Bio-concrete has global potential for fast healing. But its widespread use is currently limited to research in developed countries. To expand adoption in developing nations, challenges like cost, resources, skills, and health risks need to be addressed through research and skill development.

The above outcome is favorable indicating the exploration of its in-depth behavior at large scale. Complete investigation and experimental research can make implementation of bio concrete successful in real-life structures. The issue of cost (a major hurdle in the application of bio concrete) can be overcome, once the experimental research will be completed.

Declaration of Conflict of Interests

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