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Short communication

Physical, strength, durability and microstructural analysis of self-healing concrete: A systematic review

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ABSTRACT

Cracks are one of the worsening reasons for concrete failure, which permits the penetration of chemical solutions and could significantly impact the physical, mechanical, and durability characteristics of concrete buildings. To protect, heal and assimilate concrete structures, numerous coating materials, binding materials, and adhesives have been generally exercised. Though these methods are highly appropriate, because of their different essential procedure, critical issues, for instance, lack of effectiveness in cost and delamination, have caused the exploration of substitute procedures for sealing cracks and self-healing concrete. One of the newer self-healing methods is employing bacterial material modified with precipitation of calcite in concrete mixes to fill or heal cracking in concrete. In this method, the mineralization of bacteria is carried out via the decomposition of calcium and urea to form calcium carbonate, which could fill the cracking. To review the methods for this kind of precipitation, the present paper aims to offer an in-depth study of precipitation of calcium carbonate, physical, mechanical, and durability characteristics, and micro-structure performance of concrete. One hundred fifty articles were studied to perform the present study. Their results have been presented about the dose and type of bacteria and its impact on strength and durability characteristics. The present study shows that bio-mineralization largely relies on several factors, for instance, the preservation of bacterial cells and the application procedure. Furthermore, the impact of bacterial material on the environment is observed to be straight related to the proportion of urea in concrete mixes.

1. Introduction

Cracking in concrete is unavoidable because of its comparatively reduced tensile capacity and the action of various loading conditions [1–3]. Causes of cracks could be diverse with dry and plastic shrinkage, external loads, thermal stresses, steel reinforcements rust, or coupled influence of several factors [4–6]. For instance, micro-cracks could develop because of the shrinkage but could pierce

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at the reduced stress stage when external forces are applied, and it causes a chain of cracks [7–9]. These chains of cracks provide an easy way for water and other detrimental liquids to penetrate the concrete and chemically damage concrete. These issues are worse in areas with high precipitation and humidity in the air. Cracks in concrete could be fixed physically, but there are different issues linked

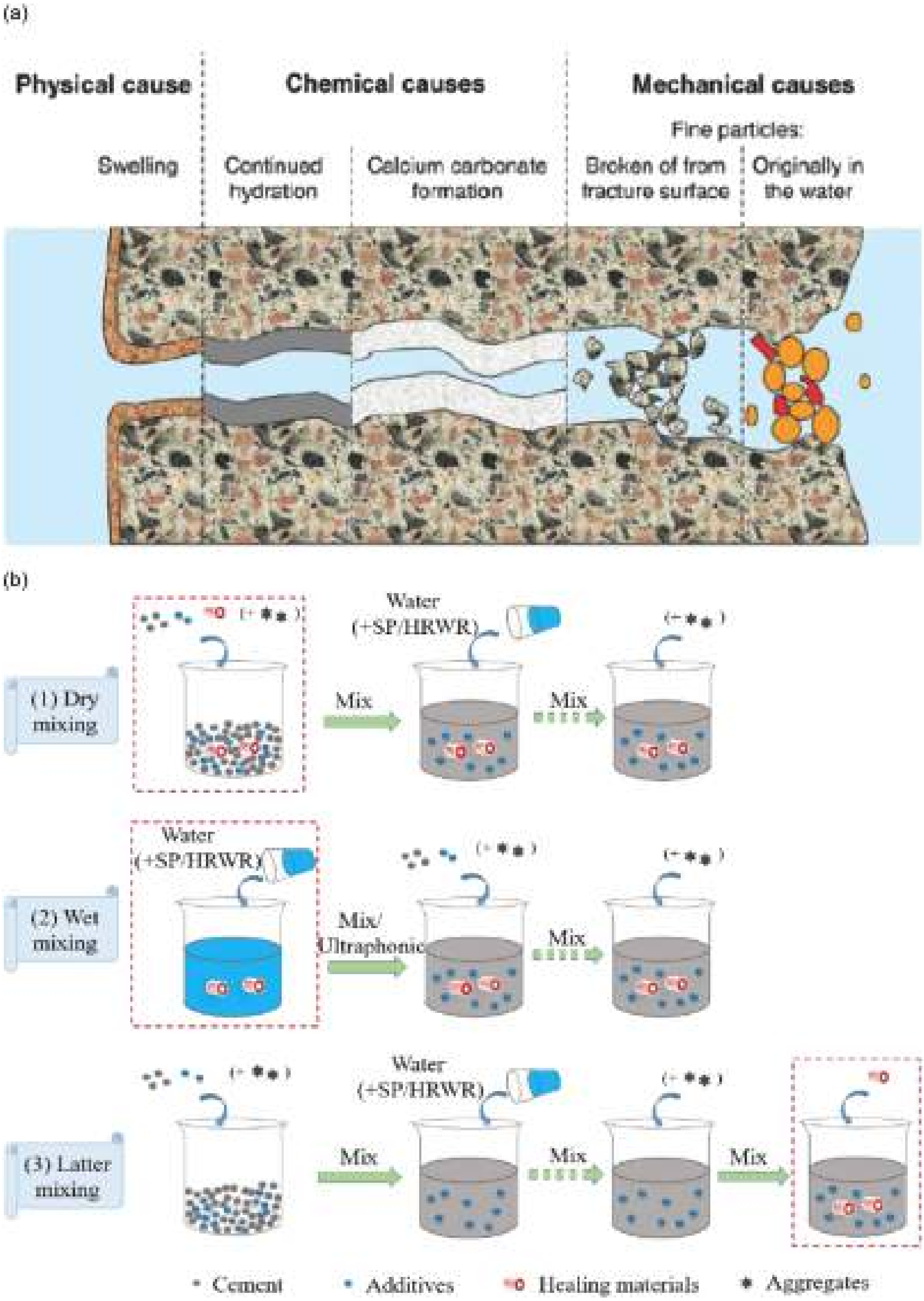

Fig. 1. (a) Mechanism of autogenous healing of concrete. (b) Three different methods for mixing Self-healing concrete
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with the physical repair and maintenance of concrete, for instance, the effect on the budget, cost, surroundings, and convenience. Several repair materials based on cement and chemicals exist in the market [4,10–12]. Cement manufacturing is the reason for nearly 7% of worldwide carbon dioxide outflow [13]. At the same time, chemical-based repair materials cause incompatibility issues with health-related concerns and materials [14]. Micro-cracks could instigate in samples right after construction or later, which is sometimes overlooked until it causes significant structural and durability-related problems. It is also heavy on a budget to perform routine repair activities on buildings and structures. Hence, there is a demand to explore a sustainable method of healing cracking that comprises lesser cost and removes the physical need for involvement [15–17]. Self-healing of concrete (SHC) is a developing idea of offering high-quality materials combined with the ability to repair cracks. Its application has received much appreciation from the construction sector. Hence, the mechanism of self-healing might be capable of significantly lower the repairing and maintenance costs. Self-healing in concrete can be classified into two groups. The first is autogenous healing, and the second is autonomous healing. Autogenous healing is caused naturally by binding materials, i.e., further hydration of un-hydrated Portland cement, whereas autonomous healing needs a trigger to activate the mechanism of healing [18,19]. The mechanism of autogenous healing is displayed in Fig. 1(a) and recognized as: (a) carbonation of Ca (OH_2), (b) obstruction of cracks led by the loose particles of concrete because of the cracking and impurities in water, (c) Expanding of a hydrated matrix of concrete in sides of cracks, (d) continuous hydration of binder particles [20,21]. The effectiveness of autogenous healing could be improved by adding different types of fibers, supplementary cementitious materials (SCMs), fillers, and other curing materials. Contrasting to autogenous healing, autonomous healing depends on embedded untraditional inclusion instead of an un-hydrated binder and is likely to repair huge cracks. Several procedures of autonomous healing have been worked on, counting with bacteria, capsule or vascular in concrete, shape memory alloy and electro-deposition technology. In all these procedures, electro-deposition is appropriate for repairing concrete structures built around marine environments because it needs electricity, electrolytes, conductors, etc. The existence of cracks usually instigates capsules or vascular in concrete, while self-healing of concrete with shape memory alloy requires thermal insulation. Though autogenous and autonomous healing can only repair any concrete in which the cracks are within the limits of only some micrometers, it cannot repair the whole structural damage of any building or structure. Currently, the mechanism of sustainable self-healing concrete (SHC) utilizing microbial modified precipitation of $CaCO_3$ has been largely studied to close and heal the cracking. Bacillus Sphaericus (BC) is a material formed from the decomposition of urea by ureo-lytic bacteria, it is recognized as inoffensive to humans. Furthermore, it's utilization in concrete lowers the possibilities of corrosion of steel reinforcement.

The mixing amount of SHC is generally evaluated as per the mixing method of traditional concrete. The addition of materials with swelling properties or nano-materials will lower the fresh properties of concrete because of the water absorption [23]. Usually, mineral fillers are introduced as a fractional replacement of Portland cement, which leads to a marginal reduction of Portland cement. Still, the strength characteristics of concrete could enhance or degrade depending upon circumstances [24]. Past studies [25,26] showed that process, speed, and mixing time significantly influence concrete's workability and strength properties. Hence, adopting an appropriate method for mixing and dispersion of biological materials in concrete is essential. As per the mixing situations of healing material, the mixing process for SHC can be classified into wet, dry, and latter mixing, as presented in Fig. 1(b). Brittle healing materials must be entrenched in concrete at the last stage of mixing to protect them from breakage during fabricating concrete [27]. Moreover, the basalt, glass, and steel fibers are introduced to avert the brittle failure of SHC during the cracks' formation and control the crack width [28].

The coating is a highly suggested and appropriate technique to improve concrete structural durability [30]. Present research on using the coating technique has depicted promising outcomes with the likelihood of employing microbial calcification to address the said problems [31,32]. The general procedure of adding bacterial material to concrete is grounded on the putrefaction of calcium and urea to form $CaCO_3$ [33]. It is observed that when bacterial material is appropriately applied to the cracked surface of concrete, it can close cracking with the highest width of 0.47 mm [34]. Compared to autogenous healing over the utilization of un-reacted binding materials, which is quite efficient in repairing the highest cracking of 0.15 mm [35,36]. Furthermore, the healing tempted by the microorganisms could decrease permeability [37], repair microcracking, and improve the mechanical characteristics (with 39% and 68% enhancement in flexural and compression strength [38,39]) of concrete because of the filler impact of microorganisms and improving the imperfections on a microstructural level in concrete.

Three distinct techniques are utilized for using the bacterial materials in concrete, bacteria encapsulation in the mix to keep the bacteria latent till it is activated, injecting or spraying the bacterial material on the concrete's surface, and direct inclusion of bacterial material to the mix [40]. It must be ensured that the alive cells can grow and react; organic food, such as urea [19] and yeast extract [20], should be provided in closeness to bacterial material. Furthermore, calcium carbonate's bio-mineralization and calcification usually happen in 2 fundamental kinds of heterotrophic and autotrophic precipitation of calcium carbonate [41,42]. As the concrete mix has a pH of near 12, only specific types of alkali-philic-based bacterial material are appropriate for forming calcium carbonate [43]. Though some review articles on the formation and utilization of bio-based concrete [44], most of these articles focus on the direct influence of adding bio-material on the concrete's mechanical characteristics. Furthermore, those articles' durability, characterization, and micro-biological attributes of bio-based concrete are overlooked and only describe the improved strength characteristics due to the addition of bacterial material. Gupta et al. [44] reviewed and emphasized four main features that evaluate the efficiency of bacteria-based self-healing (SH) characteristics, which include the ability to seal and repair the cracks, impact of the inclusion of bio-materials on characteristics of concrete, encapsulation, and persistence of capsule throughout the mixing of concrete. Griño et al. [45] wrote a review article on bio-effected SH procedures in concrete and just fixated on assessing the tests performed and determining the study novelty in this domain; however, they didn't offer a thorough study of concrete's characteristics. However, these studies did not use bio-based materials to study concrete's microstructural mechanical and durability characteristics.

1.1. Significance of present work

The present review article thoroughly studies applying bacterial material to concrete. It then emphasizes different types of bacterial material, their effects on concrete, and their corresponding outcomes on the mechanical strength and durability characteristics. For the purpose of comprehensiveness, cost and environmental-related challenges are also discussed. More than 150 research/review papers have been studied in the present review article, and their test outcomes were obtained and presented here. The present review article offers a thorough study of the key variables impacting the failure and success of bacteria-based concrete.

2. Bacteria-based self-healing method (SHM)

An excellent SHM should be able to sense the cracking that could set off the release of the biological healing material. SHMs are perfect techniques for rehabilitating concrete micro-cracks. Mechanisms of autogenous healing display excellent outcomes in repairing the concrete's surface cracks. Including bacterial material will make a layer on the concrete cracks that follow the precipitative layer of $CaCO_3$ [43,46]. As concrete is naturally alkaline, the added bacteria can withstand alkaline surroundings [47,48]. Biologically modified $CaCO_3$ precipitation assists in filling the micro-cracks and binds other concrete ingredient materials, e.g., aggregates and sand [49]. The contribution of microorganisms in the precipitation of calcite could enhance concrete durability. By converting urea into carbonate and ammonium, BC could precipitate calcium carbonate in highly alkaline surroundings [50]. A crack in concrete less than 0.3 mm could be repaired and filled by concrete by itself. When the cracking in concrete is more than 0.3 mm, the concrete cannot fix the cracks by itself, which creates a pathway to detrimental substances. In SHC, the development of cracks causes the bacterial agent's activating from its hibernation phase. By the bacterial agent's metabolic act, through the self-healing method, $CaCO_3$ infiltrates into concrete cracking and thus heals them. When the crack is filled with $CaCO_3$, the bacterial material returns to its hibernation phase. When the cracks are developed, the bacteria start to heal the cracking. Bacteria behave as a long-term healing material; this procedure is known as micro-biologically produced calcium-carbonate precipitation (MPCP). The bacterial cell wall is negatively charged, and the bacterial agent draws cations from the surroundings, in conjunction with $Ca2+$, to deposit on their cell surface. The cations react with the carbonate ions to precipitate $CaCO_3$ at the cell's surface, which acts as a nucleation site. Fig. 2 displays the precipitation of $CaCO_3$ on the cell wall of the bacterial agent.

Many bacterial materials can contemplate the development of $CaCO_3$ per their metabolic trails, as provided in Table 1. It is revealed that precipitated $CaCO_3$ is very plentiful in the heterotrophic method compared to the autotrophic process. Autotrophs form composite organic compounds from subtle elements, such as carbohydrates, usually utilizing energy from light or chemical reactions. At the same time, heterotrophs require an organic source of carbon for their development [44,51]. Bacterial and encapsulation materials utilized in bio-based SH purposes have been outlined in Table 2, with significant findings from past research.

Different micro-bacterial agents can precipitate $CaCO_3$ by the method called urea lysis. A detailed examination of past studies has suggested some usages of bacterial agents. Bacillus Aerius bacterial agent in wheat straw ash concrete was examined and noted that the concrete's durability had been enhanced. The Bacillus Subtilis bacterial agent could improve the concrete strength with graphite nano-platelets (GNP) and lightweight coarse aggregates (LWA) [58,59]. The Sporoscarcina Pasteurii [SP] bacterial agent utilized in silica fume concrete has enhanced durability and strength through a self-healing mechanism [60]. The SP bacterial agent utilized in fly ash concrete revealed an enhancement in concrete's durability and strength through the self-healing method [31]. Bacillus Megaterium (BM) bacterial agent was utilized in concrete, and test outcomes showed a 25% enhancement in compression strength [61]. The

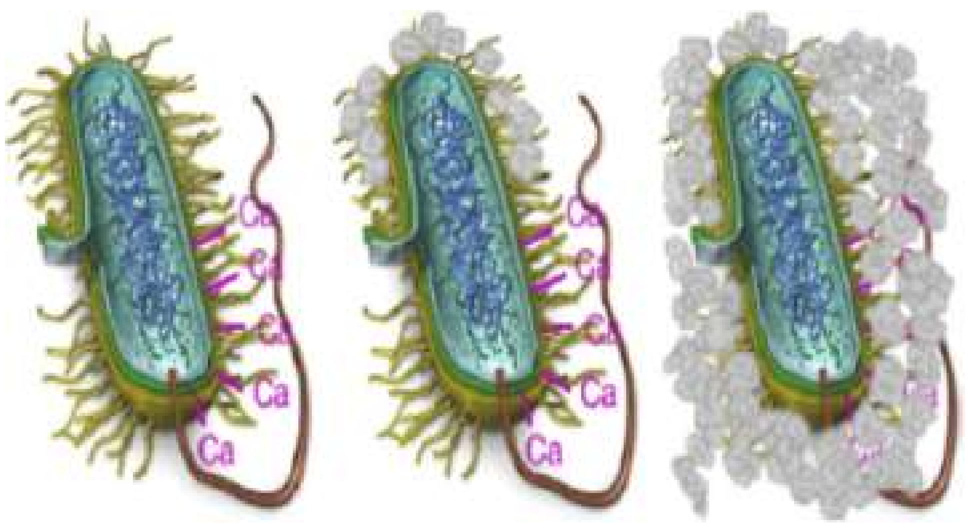

Fig. 2. Development of CaCO3 on the cell wall of bacteria
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Table 1
Several metabolic ways of precipitation of bacteria-based $CaCO_3$ [44].

Auto-trophic bacteria	Heterotrophic bacteria				
Non-methylotrophic methanogenesis	Assimilatory pathways	Dissimilatory pathways			
Oxygen based photosynthesis	Decomposition of urea	Organic carbon oxidation			
		An-aerobic		Aerobic	
		Method	e-acceptor	Method	
Oxygen based photosynthesis	Amino acids' ammonification	Reduction of NO_x	NO_2/NO_3	Oxidation of methane	O_2/CH_4
		Reduction of Sulfate	SO_4^2	Respiration	O_2

Table 2
Reviews of different bacterial and capsule materials utilized and their role in concrete healing.

Species of bacterial material utilized	Capsuled material	Mechanism	Directly included	Significant outcome	Ref.
Bacillus subtilis	LWA and GNP	Decomposition of calcium lactate	Yes	(a) LWA is more effective when specimens are damaged prior to later phases of curing (14 and 28 days) (b) the bacterial agent could be distributed equally in a sample when immobilized in GNP because of finer particles and equal distribution of GNP.	[52]
Bacillus Sphaericus	Bacteria (one dose) Hydro-gel (one dose)	Decomposition of ureolytic of calcium nitrate	Yes	70% reduction in permeability for a sample comprising encapsulated hydro-gel and bacteria	[53]
Bacillus Sphaericus	Diatomaceous earth (DE)	Decomposition of ureolytic of calcium nitrate	Yes	The amount of DE should be carefully attuned because it could result in the reduction of the workability of concrete	[23]
Bacillus cohnii	Clay aggregates	Metabolic alteration of calcium lactate	Yes	(a) No loss in feasibility for up to 5 months (b) crack length of 7 cm and width up to 0.15 nm was fully healed.	[54]
Spore-making bacterial agent	Hydrogel	No revealed in a research study	No	(a) It was observed that when the age of cracking is high, the possibility of healing will be low (b) Early healing was noted with water curing of the sample	[55]
Bacillus Sphaericus	Immobilized in silica gel	Decomposition of ureolytic of calcium nitrate	Yes	(a) High activity of bacterial agent was observed in a solution of silica (b) High recovery of strength was noted in the sample	[56]
Bacillus Sphaericus	Melamine-based capsule	Decomposition of ureolytic of calcium nitrate	Yes	(a) Permeability was observed to be ten times lower than the reference sample (b) The ratio of healing of cracks was observed to be ranging from 50% to 85% for cracks with a width of 980 μm	[57]
Bacillus Sphaericus	Hydrogel based on sodium alginate	Decomposition of ureolytic of calcium nitrate	Yes	Activity for bacterial materials was only noted for encapsulated specimens with the face of cracks determined with consumption of oxygen	[58]

deposition of $CaCO_3$ in concrete by BS enhances concrete durability [62]. Bacillus Sphaericus bacterial material was utilized in concrete to check the surface treatment. The test outcomes revealed that bacterial calcium carbonate precipitation could be used as a substitute for concrete surface treatment [63].

3. Procedure of applying the bacterial-material to concrete

According to past studies, the bacteria material could be applied to concrete using direct procedure and encapsulation. Past studies showed the usage of bacterial material in concrete by including healing agent in LWA and GNP; it is noted that graphite nano-platelets is a decent compound carrier for bacterial material and has provided good outcomes in repairing cracks [52]. The usage of healing material by the direct technique is utilized for determining an optimal concentration of bacterial material for strength purposes, and the optimal concentration of bacteria was revealed to be 28×10^5 cfu/ml [61]. Another proposed technique is the infusion of LWA by a bacterial agent and then its encasement in a polymer coating layer based on improving the overall performance of self-healing concrete [64]. Fig. 3(a) presents the SHM by utilizing the micro-encasement technique assimilating healing material for self-healing (SH) of concrete. When the crack breaks the rooted micro-encapsulation, the healing material is released into the faces of cracks by utilizing capillary action. The healing bacteria links with the rooted catalyst, which activates the polymerization process and protects the closing of the nearest cracking. Fig. 3(b) illustrates the generally cracked micro-capsule [65]. Encapsulation by hydro-gel (HG) technique was also utilized, and the samples with the HG-rooted healing agent had an enhanced SH efficiency regarding precipitation content and cracking healing [66]. The SH by encapsulation method can offer first-rate SH regarding the wider width of cracking that could be healed and the earliest reaction to cracking in the matrix [67]. The direct technique of applying the bacterial agent to concrete

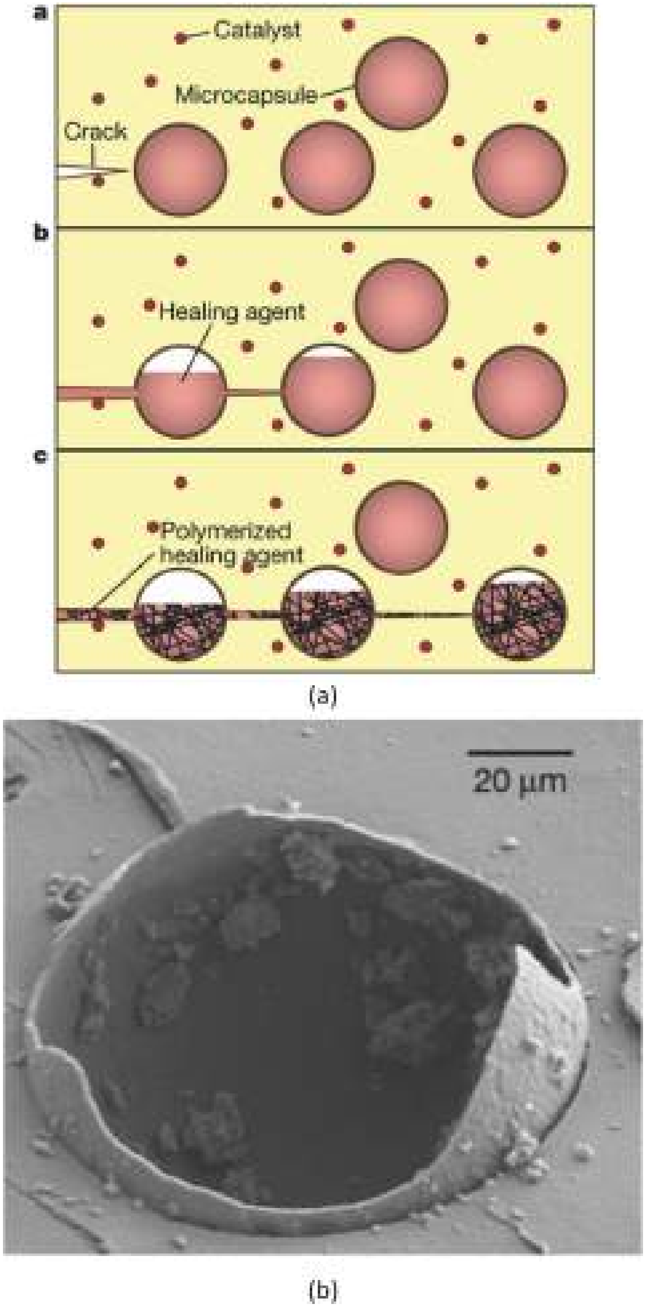

Fig. 3. (a) Simple method of micro-capsule technique: (i) development of cracking in the matrix; (ii) method of discharging healing material; (iii) Healing agent working in a matrix and (b) SEM micrograph showing a cracked micro-capsule.
(b) Used as per permission from Elsevier [29].

was examined, and the test outcome revealed a 30% enhancement in compression strength in Portland cement mortar at 28 days [68]. Based on past studies, the encapsulation technique showed more effectiveness in SH regarding the closing of cracking and the content of precipitation of $CaCO_3$, which is because of unvarying spreading and bacterial protection in the alkali surroundings. The technique utilized for healing, depth and width of crack can be heal by utilizing the technique as presented in Table 3. The significant drawbacks and advantages of utilizing encapsulation and bacterial agent techniques are showed in Table 4.

4. Molding and curing technique of bacterial-based concrete

The molding method of SHC is generally similar to normal concrete. Usually, fresh concrete is discharged into different layers, and

Table 3
Methods of self-healing and examined variable.

Method	Width of cracks	Depth of cracks	Ref.
Bacteria and encapsulation	Healing of the highest cracking width of 0.965 mm was noticed	–	[53,56,69]
Micro-encapsulation	–	The highest cracking depth of 40 mm was healed	[70]
Direct application of bacterial agent	–	The highest cracking depth of 31 mm was healed	[71]

Table 4
Summarized difference in specific methods [72].

Method	Advantage	Disadvantage
Encapsulation	1. Highly effective under different measures of damage	1. Difficulty in discharging healing material
	2. The healing material discharges when required	2. Complex in preparing
Bacteria	1. Biological active, free from pollution, and fully natural	1. Precaution should be followed to protect the bacterial agent in the concrete sample fully.
		2. Different basics to be followed.

mechanical vibration is performed on every layer. Other types of curing techniques have been studied by several researchers [73–76]. Fig. 4 shows a summary of several curing techniques in 2 phases. Several curing methods are planned to try different surroundings and study their impacts on self-healing. Water is essential to improve SH for autonomous and autogenous healing in concrete, and higher moisture is insufficient to guarantee SH [77,78]. Still, water as an alternative to flowable water curing leads to a quicker decrease in perviousness coefficient and an even higher reduction in the width of cracking in mortars with mineral admixtures. This may be due to flowing water leaching the calcium and hydroxide ions, reducing the pH value and ions of calcium concentration necessary to develop healing products [79]. Sisomphon et al. [24] noticed the curing technique of cycles of water to air assisted in an improved self-healing performance of the binder composite's strain hardening. The authors recognized that one reason for the enhanced impact of wet and

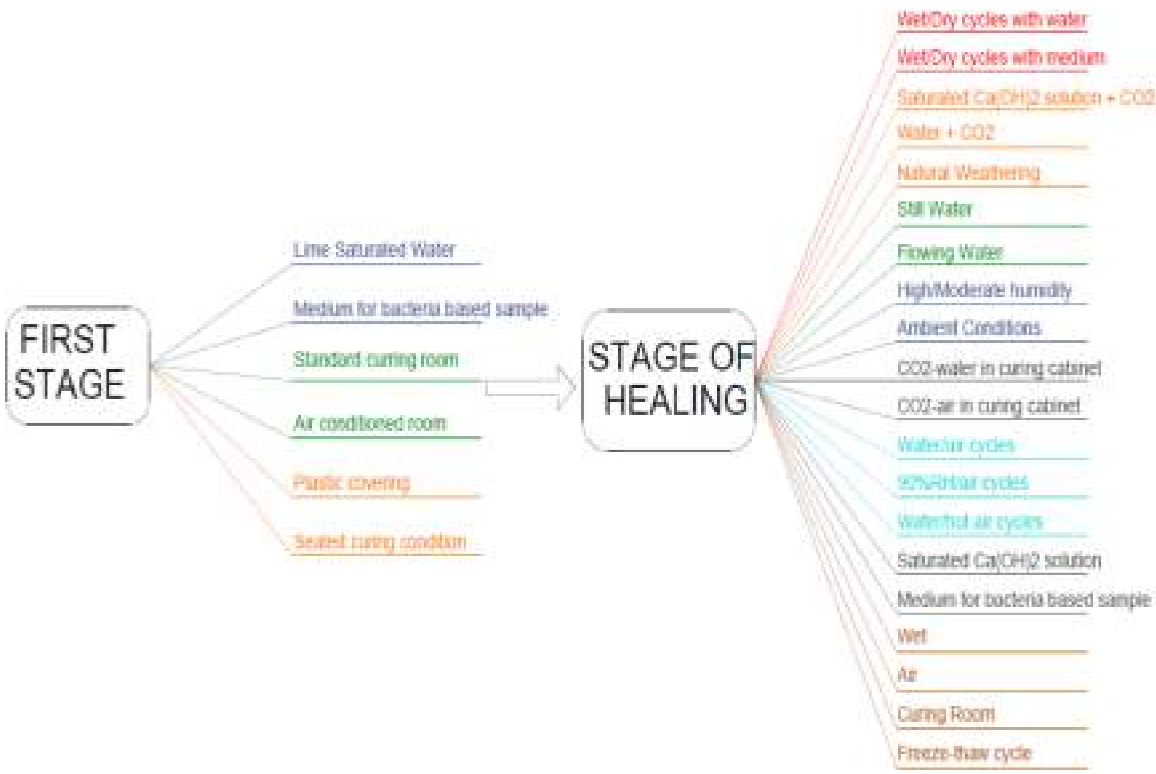

Fig. 4. Condition of curing at primary and self-healing phases.

air cycles of curing was the evaporation of extra water through the dry curing, which resulted in enhancement in the concentration of ions in cracks, improving chemical reaction, hydration, and precipitation. Another cause was noted to be the infiltration of carbon dioxide into cracks through the drying period of curing, which further enabled the development of carbonates [24]. Water curing generally assists bio-based concrete to attain a high ratio of healing of cracks, higher to wet and air curing [55]. Medium deposition as a healing condition appears to be better than water for bio-based concrete in terms of repairing cracks and water absorption [55].

5. Influence of bacterial material on the characteristics of concrete

5.1. Hydration properties

The inclusion of bacterial agents in powder form in concrete samples either quickens or slows the concrete's setting time reliant on the proportion of source of calcium provided. The nutrients to the bacterial agent are provided in the shape of calcium formate, calcium lactate, calcium nitrite, calcium nitrite, and calcium formate could shorten the concrete's setting time, and calcium lactate could slow the setting time [80,81]. In past research [34], the authors noted that continual hydration or precipitation of calcium carbonate is the motive behind the closures of cracks for self-healing concrete [28], while the crack healing process of SHM comprising capsule could be different from each other and rely on the healing materials present in the matrix [50]. Self-healing concrete with completely healed cracks has been observed in the past literature [82,83]. Yang et al. [84] revealed that temperature curing of SHC led to improved performance due to the accelerated hydration in the concrete matrix. As some of the bio-materials are nano size, it improves the concrete's hydration due to the nucleation site of hydration products in the pore solution [85]. Calcite's precipitation by continual binder's hydration assist in the development of $CaCO_3$ precipitation. The impact of ureolytic bacterial material such as Bacillus Pasteurii on self-healing concrete assists in calcite production by continual hydration in SHC [46]. Various sources of calcite could be used for calcite's precipitation by the recurrent hydration of the non-hydrated particles of Portland cement in the self-healing concrete [86]. The precipitation of calcium carbonate is governed by the concentration of calcium and carbonates, pH and the existence of nucleation site.

5.2. Compressive and flexural strength

Concrete strength has been enhanced by bio-technique based on calcite precipitation. Microbial cells achieved decent nourishment during the primary curing, as the binder mortar was porous. These microbial cells were adjusting to a new environment. Because of the high Portland cement pH level, there is a likelihood for microbial cells to develop gradually in the primary phase and adapts to the higher pH situations in the curing phase. Through the development of the cell, calcite precipitates on the cell's surface and in the matrix of binder mortar, which might be because of the different ions in the matrix. This causes lower penetrability and permeability of binder mortar. Oxygen and nutrient movement to the bacteria cells stops if more pores in the media are plugged at that duration. With time, the cells get dead or transform into endospores. Hence the performance of enhanced compression strength with microbial cells could be clarified [87]. By adding BM bacterial agent by 28×10^5 cfu/ml in concrete, calcite precipitation was higher in advanced grade concrete (AGC) than in low-grade concrete (LGC). So AGC offers the additional capacity for concrete in comparison with LGC. The highest rate of strength advancement for AGC of 45 MPa sample is higher than 25% in strength [61]. Portland binder was substituted with silica fume, and 10^5 cells/ml Sparcious Pasteurii bacterial agent was added. An 18% improvement in silica fume concrete's compression strength was noticed because of the deposition of $CaCO_3$ on the micro-organism's cell surface [60]. The compression strength of bacterial-based silica fume concrete is enhanced because of the $CaCO_3$ precipitation. A microstructural study of a concrete sample utilizing x-ray diffraction and scan electron microscopy showed that CaCO3 was exiting in the concrete [31]. The compression strength of the sample with Sparcina Pasteurii combined with Bacillus subtilis bacterial agent is 18% more than the sample with no bacterial agent at the curing of 28 days [69].

Portland cement was substituted with different doses of silica fume of 15%, 25%, and 35% in a mortar; bacteria cells enhanced the compression strength of mortar by 20%, 15%, and 9% compared with the reference sample [88]. Graphite nano-platelets behaved as a decent compound carrier for unvarying bacterial agent spreading, resulting in higher effectiveness in the healing of cracking. With the

Table 5
Different kinds of bacterial agents and outcomes of their compressive strength.

Bacterial agent utilized	Optimized test outcome	The proportion of Bacterial agent	References
Shewanella Species	30% enhancement in mortar's compression strength in comparison with a reference sample	95000 cells/ml	[68]
Sporoscarcina Pasteurii	More than 30% enhancement in compression strength of mortar was attained over than normal sample	10^5 cells/ml	[31]
Bacillus subtilis	Increase of more than 10% in compression strength than reference specimen with LWA	3.0×10^8 cells/ml	[52]
Bacillus sp. CT-5	Increase of more than 38% in compression strength to reference concrete	6×10^7 cells/ml	[71]
AKKR5	Increase of more than 10% in compression strength than reference concrete	10^5 cells/ml	[90]
Bacillus Aerius	Enhancement of compression strength of more than 12% in bacteria-based concrete in comparison with the sample having 10% rice husk ash	105 cells/ml	[91]
Bacillus Megaterium	Strength was developed by 25% in high grade 50 MPa concrete	25×10^5 cells/ml	[61]

inclusion of Bacillus subtilis with the Graphite nano-platelets, the concrete's compression strength was enhanced in all phases because of the $CaCO_3$ microbial precipitation [52]. The compression strength at the curing of 28 days was enhanced when contrasted with the reference sample by adding reactive powder in spores form in a mortar sample [80]. Deposition of the $CaCO_3$ on the surface of cells and in the matrix of binder-sand connects the matrix in the mortar and leads to the enhancement in the compression strength by bacillus subtilis [89]. Table 5 provides the details of the bacterial agent utilized, the values of compression strength, and the proportion of bacterial agent used; these may fluctuate depending on the source of calcium supplied to the bacterial agent.

The elementary process of restoring strength and repairing cracks in bio-based concrete is the conversion of soluble organic nutrients into inorganic crystals of calcium carbonate that heal the cracking [39]. Recent research has depicted that cracking repairs over calcium carbonate depend on different factors that can be split into chemical and physical properties. In chemical properties, the concentration and kind of bacterial material [39], nucleation position for the bacteria immobilization [47], and medium of pH [41] are the highly influential factor in the formation of strength. It is observed that the maximum compression strength was attained when the scope of bacteria dose was 10^4 to 10^7 cfu/ml [41]. Furthermore, the type of bacterial material can also be vital in strength numbers. Rauf et al. [21] noted that Bacillus Sphaericus (BS) showed a maximum recovery in strength compared to Bacillus Subtilis and Bacillus Cohnii because of the BS's maximum precipitation of calcite. Rauf et al. [41] and Chen et al. [41] observed the bacteria's immobilization utilizing natural fibers and Ceram site as carrier composites to inspire precipitation of calcite modified by microbes. Their study observed that appropriate immobilization methods could enhance bacterial concrete's flexural strength by 55–68%. They also noted that natural fibers could protect the concrete against the alkaline materials within the concrete mixes and could further enhance the compression strength by 39%. The enhancement in strength could be ascribed to the capability of carriers to shield and offer nutrients to bacteria to make calcium carbonate for repairing cracking and sealing pores [40].

One of the added variables impacting the bacteria-based concrete's compression and flexural strength is the nutrients utilized as a source of food for bacterial material, for instance, yeast extract, calcium nitrate, urea, and calcium formate. Qian et al. [80] assessed the dose of calcium nitrate, calcium lactate, and bacterial spore powder on the impact of bacteria-based concrete's compression strength. It was noted that using calcium lactate with bacterial spore powder slowed the hydration process and extended the setting time. Schreiberová et al. [92] assessed the impact of nutrients of bacteria on the strength characteristics of bacteria concrete. They observed that adding yeast led to a significant reduction in compression strength. For instance, urea, calcium formate, calcium nitrate, and calcium lactate marginally enhance the concrete's compression and flexural strength numbers [92]. Nevertheless, the physical attributes impacting the mechanical characteristics of bacteria concrete are very different and add a variety of mixed procedures of gaining strength to the conventional concrete, with bio-based material acting like a possible filler at the primary phases of hydration [93]. The physical characteristics of cracking in bacteria concrete are crucial in healing. It was noted that cracking with a width of more than 0.5 mm has a considerably lesser capability of healing cracks regardless of the curing procedure [94], which is because of the possible shortage of appropriate minerals and the immobilization of bio-based materials. Table 6 provides comprehensive detail of compression strength (CS), splitting tensile strength (STS), and flexural strength (FS) test outcomes of self-healing concrete with the incorporation of Bacillus subtilis.

Table 6
Mechanical Strength test outcomes of present researches that employed Bacillus subtilis for self-healing of concrete.

Mix Design				Curing conditions	Mechanical Strength (MPa)						References
Concrete		Bacteria			Curing at 7 days			Curing at 28 days			
Admixture (kg/m^3)	W/C ratio	Dosage (cfu/ml)	Type of concrete		CS	STS	FS	CS	STS	FS	
1.1	0.46	0	Control	–	17	2.3	3.78	24.9	3.14	4.69	[95]
1.1	0.46	10^5	Bacillus subtilis	–	18.3	2.49	3.96	26.4	3.34	4.78	
1.15	0.55	0	Control	Water cured	–	–	28.7	–	–	–	[96]
1.15	0.55	10^5	Bacillus subtilis	Water cured	–	–	30.6	–	–	–	
1.2	0.59	0	Control	–	25	–	34	–	35	–	[97]
1.2	0.59	10^3	Bacillus subtilis	–	35	–	47	–	38	–	
3.95	0.38	0	Control	Water cured	25	1.34	–	34	1.65	–	[98]
3.95	0.38	10^7	Bacillus subtilis	Water cured	27	1.74	–	37	2.03	–	
3.68	0.40	0	Control	–	17.5	–	–	25	–	–	[52]
3.68	0.40	10^8	Bacillus subtilis	–	20	–	–	26.5	–	–	
–	0.42	0	Control	Water cured	34	2.64	2.85	43	3.65	3.44	[99]
–	0.42	10^2	Bacillus subtilis	Water cured	38	3	3.40	49	3.78	3.78	
–	0.48	0	Control	–	38	4	51	6	51	7	[100]
–	0.48	10^9	Bacillus subtilis	–	48	5	48	6	55	8	
1.15	0.44	0	Control	–	–	–	28	–	–	–	[39]
1.15	0.44	$2.7\ 10^8$	Bacillus subtilis	–	–	–	29.5	–	–	–	
1.34	0.35	0	Control	Water cured	–	–	–	42.9	–	–	[101]
1.34	0.35	10^7	Bacillus subtilis	Water cured	–	–	–	41.6	–	–	
–	0.67	0	Control	Water cured	28	–	–	31	–	–	[46]
–	0.67	10^2	Bacillus subtilis	Water cured	32	–	–	36	–	–	

5.3. Modulus of elasticity (MOE)

MOE alludes to the capability of concrete to distort in the elastic stress-strain area range without cracking [102]. The concrete's elasticity usually relies on the sort and distribution of aggregate particle size [103], type of reinforcement [104], and kind and timing of curing [105]. Regardless of the considerably high effect of these factors in bio-based concrete, the proportion of bacteria is observed to impact the MOE significantly. Fig. 5 displays the change in MOE at 28 days for bio-based concrete with Bacillus Sphaericus with different levels of doses. It could be observed from Fig. 5 the rise in the amount of bacterial material up to a specific proportion led to an increase in MOE, which could be because of the improved compaction at the microstructural level in the interfacial transition zone with the raised amount of bacterial material [106]. As observed by Kua et al. [107], bio-based concrete with biochar-restrained bacterial material spores shows an enhanced MOE subsequently to cycles of healing after its cracking. Compared to healing through bacterial material, it was observed that AH, due to the un-hydrated particles of cementitious materials, inclines to reduce the MOE [107]. This could be ascribed to the decreased surface adhesion because of the possible incapability of AH to be utilized in significant cracking [107]. Reddy et al. [108] revealed that with the addition of bacterial material in self-healing concrete, the modulus of elasticity was enhanced considerably than the medium or high strength plain concrete. Also, Kua et al. [107] reported that the required modulus of elasticity could be attained by joint utilization of hybrid fibers and immobilized bio-char bacterial material. This can be attributed to the sealing of inner crack and bio-material densifying the paste-aggregate matrix by microbially induced precipitation of calcite [107].

5.4. Toughness

Toughness is defined as the material that can absorb energy and endure external force without cracking, and it is usually measured as the area under the stress and strain curve. Reddy et al. [108] observed that adding bacterial material could enhance the slope of the stress-strain curve, signifying a maximum toughness in bio-based concrete compared to standard concrete. This could be due to the progress of high stress and peak strains in bio-based concrete before cracking than in traditional concrete. In a research, the authors' analysis depicted that toughness of bio-based concrete modified with crustal admixture was regained after early curing phase and structure crack, which could be ascribed to the significant enhancement in the content of calcite [109]. Fig. 6 compares bio-based concrete's stress-strain curve and normal concrete. Tsangouri et al. [110] evaluated the impact of the addition of small capsules on the toughness behavior of self-healing concrete. Capsules were created with the adhesive-based bio-material that offered autonomous healing. The authors [110] noted that the toughness behavior of self-healing concrete was improved by 35% compared to the control concrete. Cuenca et al. [110] investigated the toughness performance of SHC and subjected the self-healing concrete to continuous cycles of cracking and healing to quantify the retaining or retrieval of strength attributes of self-healing concrete. The authors [110] observed that the toughness performance was improved due to the bridging of cracks in the concrete's matrix with the help of fibers and bio-based material. Schreiberová et al. [92] investigated the effect of the direct addition of bio-based material (yeast extract) to the concrete mix on the self-healing concrete's strength performance and noted that it has a negative impact on some of the strength characteristics (compressive, toughness) of self-healing concrete; however, it has a minor effect on the flexural strength of SHC [92].

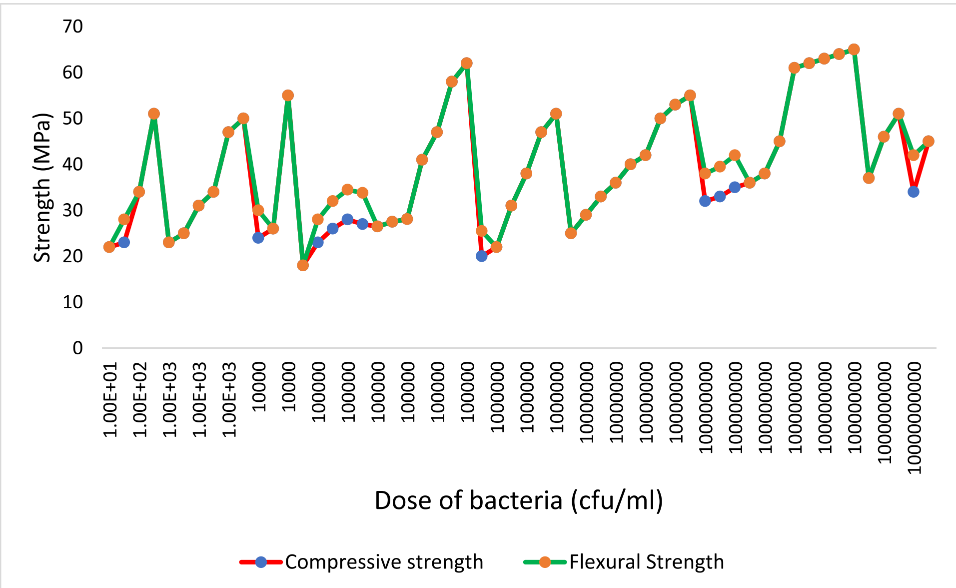

Fig. 5. Bacterial concrete's compression and flexural strength at 28 days with the various proportion of bacterial material (based on the test outcomes of 70 researches).

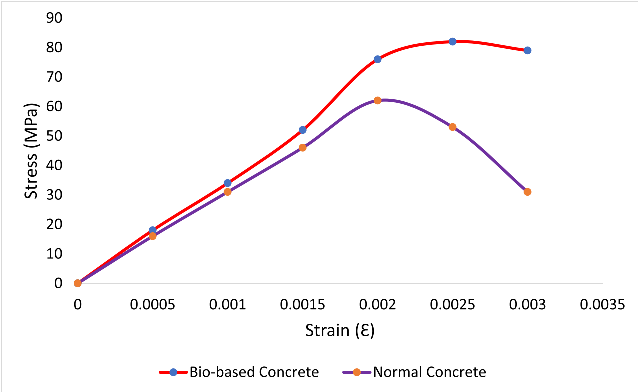

Fig. 6. stress-strain curve of normal concrete vs. the bio-based concrete with Bacillus subtilis.
Data from Reference [108].

6. Impact of curing condition on strength characteristics

Changes in curing procedures could impact the concrete's mixture reactivity and regulate the moisture content within the primary phases of compaction. The main difference in the curing condition is grounded on humidity, sealing, and temperature phases. Practically, bio-based concrete is cured in water by immersion method [111], steam [112], a medium of calcite lactate [113], and a solution of calcium chloride [114]. Among them, curing in water by immersion method has displayed the up-and-coming techniques of curing, which offer the appropriate moisture content for the growth of bacterial material [40]. Furthermore, it was observed that curing with water decreases the entire permeability of concrete by up to 18% [40] and absorption of water by 9% [115], with a slightly high electrical resistance subsequently to curing of 145 days in comparison to curing with calcium lactate [101]. It was also revealed that curing with urea and calcium reduces the bacterial concrete's durability by decreasing the mixture's alkalinity. This could be because of the raised carbonation, sulfidation, and shrinkage [101,114]. Fig. 7 presents the impact of humidity and temperature curing on 28 days of compression strength of bio-based concrete comprising Bacillus subtilis cured in water. As shown in Fig. 7, a rise in the humidity caused a marginal rise in bio-based concrete's compression strength for a specific temperature. It can also be observed that raising the temperature in a particular humidity led to improved compression strength of bio-based concrete.

7. Durability characteristics

To assess the durability properties, concrete testing procedures which add water absorption [116], penetration of chlorides [117], water permeability [101], sulfate [118], and electrical resistance [119] have worked out. Every test is explained in different parts.

7.1. *Resistance against chloride penetration*

Rusting of steel reinforcement because of the infiltration of chloride ions is one of the primary reasons behind the wear and tear of

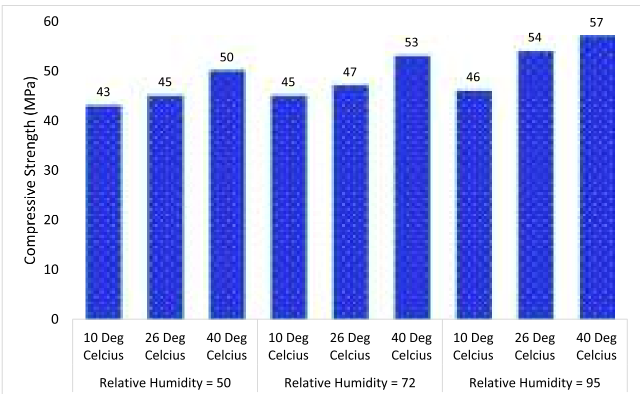

Fig. 7. The compression strength of bio-based concrete at 28 days with bacterial material with different temperatures of curing and relative humidity.
Data from Reference [99].

concrete structures. The rate of infiltration of chloride ions into the sample is majorly reliant upon the concrete's internal pore system. The pore system relies on features such as curing situation, usage of SCMs, mix design, and the degree of hydration and construction methods. The permeability of the rapid chloride test is carried out by noting the proportion of electrical current that passes over the specimen. Depending on the electrical charge passed over the specimen, a qualitative score is composed of the porosity of concrete. The resistance of concrete against the permeability of chloride ions could be improved by adding bacterial agents to concrete. It was noted that the mean no. of charge in coulombs over concrete comprising bacterial agents was 12% lesser than concrete with no bacterial agent. It was also noted that utilizing bacillus subtilis and Sparcious Pasteurii decreases the concrete's penetration against chloride ions; it also develops the behavior of decreasing mass due to sulfate and acid attacks [66]. Adding a bacterial agent to the sample could reduce the electric charge passed over the reference and rice husk ash-based concrete samples. The bacteria-based sample displayed the lowest electric charge, passed at every age of curing. Electrical charge traveled in bacteria-based samples was reduced by 54.6%, 48.7%, and 47.5% concerning reference samples at the 7, 28- and 56-days curing phase [91]. The addition of Sparcious Pasteurii with an optimal concentration of bacteria 10^5 cells/milliliter for 15% silica fume-based concrete displayed decent resistance against chloride penetration (410 coulombs) [60]. It was noted with a bacterial agent of 105 cell/milliliter concentration for every silica fume-based concrete. There was the highest decrease in chloride ions, though concrete with 25% silica fume showed infiltration of 759 coulombs, which is lower. The life span of concrete buildings open to open water or de-icing salts is well clear by the capability of concrete to fight the penetration against chloride ions [31].

The resistance of concrete against the penetration of chloride ions is accountable for the rusting of steel rebars, and it relies on the pore structure and solution [120]. It could be determined through a test called rapid chloride penetration (RCPT) [121]. Table 7 shows rapid chloride penetration test outcomes on numerous bio-based concrete. AH over the hydration of non-hydrated binding materials, encapsulation over the decrease of internal pores, and formation of calcium carbonate over the bacterial action could all possibly decrease the bio-based concrete's pores, which results in a reduction of concrete's permeability. Similarly, bacterial material could act as filling material to reduce the values of coulombs [121], confirming a decrease in concrete's permeability. This result was also ensured over the test outcomes of compression strength, signifying an improved strength and enhanced micro-structure, and further packs the matrix with the addition of bio-based material in concrete [121]. Current literature that utilized bacteria for surface treatment [122] showed a more than 15% decrease in the value of coulomb charge for bio-based concrete in 7 days of curing. Though

Table 7
Test outcome of present research on resistance against chloride penetration of bio-based concrete.

Mix design and assessed characteristics			References							
			[123]	[124]	[71]	[117]	[91]	[115]	[90]	[125]
Concrete components	Fine aggregate (kg/m^3)		570	565	680	850	570	670	645	1038
	Coarse aggregate (kg/m^3)		1158	1137	1137	574	1165	457	1345	665
	Curing condition		Water cured	–	Water cured	Water cured	–	Water cured	Water cured	–
	Water (kg/m^3)		184	185	–	162	186	165	230	210
	Portland cement (kg/m^3)		385	372	1	326	392	407	445	375
	Water to cement ratio		0.5	0.5	0.5	0.50	0.5	0.4	0.5	0.5
Bacteria	pH		10	8	8	7.3	7.5	–	8	7.5
	The proportion of bacterial material		10^5	10^6	10^8	–	10^5	10^6	10^5	10^7
Resistance against chloride penetration test (Coulombs)	7 days	Control concrete	–	–	–	2548	3304	–	3304	–
		Bio-based concrete	–	–	–	948	3034	–	3035	–
	28 days	Control concrete	2495	–	3180	2197	2367	1332	2364	–
		Bio-based concrete	1887	–	976	497	2076	1468	2077	–
	56 days	Control concrete	–	–	–	1452	1951	–	1951	5190
		Bio-based concrete	–	–	–	305	1648	–	1652	4555
Compressive strength (MPa)	7 days	Control concrete	–	31	15	28	22	28	–	–
		Bio-based concrete	–	36	16	37	25	31	–	–
	28 days	Control concrete	33	41	23	34	36	27	33	36
		Bio-based concrete	38	47	32	46	41	34	37	38
	56 days	Control concrete	39	–	–	42	38	–	39	–
		Bio-based concrete	42	–	–	56	43	–	41	–

Achal et al. [71] revealed that values of coulomb could be greater than 45% for bio-based concrete cured in a solution of urea for 28 days, signifying a considerable enhancement to resistance against chloride penetration.

7.2. Water permeability and absorption

The infiltration of detrimental materials responsible for concrete wear and tear under pressure is evaluated by permeability and thus is thought to be a significant characteristic for depicting concrete durability. This relies on the properties of the pore system of binding materials measured by permeability, size distribution, micro-cracking, and surface area. These constraints are, among others, governed by the water-to-binder ratio (w/b), infiltration of detrimental materials, curing age of hardened binding materials, and distribution of particle size [126]. The deposition of calcium carbonate in concrete caused a reduced permeability and water absorption of concrete samples. Research [31,60,90] showed that the inclusion of subtilis Pasteurii bacterial agent in silica fume-based concrete resulted in concrete's permeability and perviousness. Water absorption was revealed to decrease majorly with a proportion of 10^5 cells/ml bacterial agent in the sample. In bacteria-based concrete, the pores are filled with precipitation of $CaCO_3$ by a bacterial agent [31]. Concrete cubes were shaped with the inclusion of BM, and its nutrients engrossed twice lesser water than reference samples because of the deposition of microbial calcite [88]. Including a bacteria agent called bacillus Aerius resulted in decreased permeability and absorption because of the precipitation of calcite, which consequently enhances the concrete's durability [91]. After curing for 28 days, every reference concrete specimen displayed higher perviousness to modest perviousness. Still, the specimen with the bacterial agent showed higher perviousness to lower perviousness because the pores were filled with $CaCO_3$ [90]. Due to microbial precipitation, the water absorption of recycled aggregates in concrete can also be reduced significantly [127,128]. Concrete is a permeable material, and its porosity relies on the size and sort of pores present in the concrete. The current test outcomes in the research studies on porosity depict that cement mortar's porosity reduces with the addition of bacterial material by 27% [37] and 48% [71] Bacillus Sphaericus and Bacillus cereus correspondingly, in comparison to control mortar. This could be ascribed to calcium carbonate formation and biomaterials' filling behavior within the matrix [129]. Table 8 shows the water permeability and bio-based concrete absorption as water absorption straight connects with the porosity. Water permeability resorts to raising interlinked pores inside the pore system of concrete [130]. As observed in past studies (presented in Table 8), the inclusion of bacteria spores reduces the bio-based concrete's water permeability and absorption. Balam et al. [115] observed that curing with urea of calcium chloride led to maximum water absorption compared to water curing, limited to bio-based concrete and conventional concrete.

7.3. Drying shrinkage (DS)

The change in length over the loss of moisture, unprecedented thermal expansion, and sustained hydration are the primary limitations in repairing concrete materials that could cause constricted adhesion with formerly laid materials because of the reduced bonding. Concrete's drying shrinkage, as the change in length because of the moisture loss, is usually impacted by conditions of curing,

Table 8
Test outcomes of water permeability and absorption of literature on bio-based concrete.

Mix design and assessed characteristics			References				
			[115]	[95]	[101]	[101]	[101]
Concrete components	Fine aggregate (kg/m^3)		850	1.54	576	1031	571
	Coarse aggregate (kg/m^3)		591	2.53	394	664	1158
	Curing condition		–	–	Water curing	Water curing	Water curing
	Water (kg/m^3)		160	–	160	208	184
	Portland cement (kg/m^3)		324	1.2	445	374	387
	Water to cement ratio		0.50	0.44	0.34	0.55	0.5
Bacteria	pH		7.4	6.8	7	–	6.8
	The proportion of bacterial material		–	10^5	10^7	10^5	10^5
Water permeability	28 days	Control concrete	–	–	–	–	–
		Bio-based concrete	–	–	–	–	–
	56 days	Control concrete	–	–	–	–	–
		Bio-based concrete	–	–	–	–	–
	91 days	Control concrete	–	–	80.12	–	–
		Bio-based concrete	–	–	62.35	–	–
Compressive strength (MPa)	7 days	Control concrete	26	–	–	–	24
		Bio-based concrete	35	–	–	–	26
	28 days	Control concrete	32	–	44.29	–	34
		Bio-based concrete	44	–	41.89	–	38
	56 days	Control concrete	40	34	–	34	38
		Bio-based concrete	54	37	–	37	41
Water absorption (%)	28 days	Control concrete	2.9	7.78	7.78	6.29	3
		Bio-based concrete	2.85	5.49	5.49	6.59	1.27
	56 days	Control concrete	2.87	–	–	–	1.87
		Bio-based concrete	2.55	–	–	–	1.2
	91 days	Control concrete	2.71	6.95	6.96	6.72	–
		Bio-based concrete	2.38	5.61	5.61	5.91	–

the proportion of superplasticizer, and the water-to-binder ratio [131]. Fig. 8 depicts the collation amid bio-based concrete's drying shrinkage with Bacillus Licheniformis and Bacillus Sphaericus and control concrete; it was revealed that the inclusion of bio-based material (see Fig. 8) [124] and the existence of added chemicals with ions and nutrients resulted in an enhanced initial concrete's drying shrinkage. Still, the test outcome of research performed by Beltran et al. [132] on confined drying shrinkage depicts that bio-based concrete has a high fracture resistance compared to normal concrete. Beltran et al. [132] also showed that normal concrete has four times more delamination (separation into constituent layers) than bio-based concrete. This result is summarized because of the high-stress relaxation and creep of bio-based concrete that take care of stresses in drying shrinkage, which makes bio-based concrete highly appropriate for repairing cementitious materials.

7.4. Carbonation

It is a chemical-physical mechanism that happens through the infiltration of carbon dioxide and the development of carbonic acid, which chemically reacts with Ca $(OH)_2$ and calcium-silicate-hydrate to make calcium's carbonic salt [134]. The development of carbonation relies on the pore system, the ambiance of carbon-dioxide levels, temperature, the proportion of mixture, and humidity [135]. It was noted that the humidity level (around 55–75%) is highly promising for carbonation [135]. Fig. 9 presents the carbonation depth of bio-based and normal concrete under numerous curing conditions. It was observed that concrete's depth of carbonation comprising bio-materials and cured in water was reduced by 26%. In contrast, the normal concrete cured in calcium lactate had a considerable carbonation depth [29], as presented in Fig. 9. This result was because of the low pH and acidity of the matrix, whereas calcium lactate was sustained on surface pores, decreasing the pH and instigating a raised depth in carbonation [136]. In bio-based concrete, the formation of calcium carbonate averts carbonation, which signifies the sort of curing procedure in bio-based concrete [101].

7.5. Resistance against sulfate attack

Sulfates symbolize concrete's chemical and physical susceptibility to crystallization of sulfate salt, and it is one of the main causes of spalling, efflorescence, and concrete cracks [137]. The development mechanism of the crystallization stage of sulfate salt, which results in the buildup of salt, happens with the sulfate in the groundwater, sulfate comprising sewage and sea-water that chemically reacts with Ca $(OH)_2$ [138] and could tempt considerable pore-stresses in concrete [139]. Nosouhian et al. [66] researched the capability of bio-based concrete cured in a solution of calcium chloride urea against sulfate attack and magnesium sulfate. The authors observed that concrete cured in a solution of urea is highly susceptible to sulfate attack and change in mass of concrete in comparison to water cured sample due to the chemical reaction amid calcium chloride with magnesium sulfate inside the bio-based concrete [66]. Still, bio-based concrete was noted to show considerably less change in mass, spalling, scaling, and expanding conduct because of the absorption of sulfates and lesser porosity than normal concrete [140]. Fig. 10 depicts the outcome of sulfate resistance by Chaurasia et al. [118] on normal and bio-based concrete comprising Bacillus Cohnii, Bacillus Pasteurii, and calcium lactate. As observed from Fig. 10, bio-based concrete had nearly 30%, 38%, and 45% lesser concentrations of sulfate ions in comparison with normal concrete.

8. Microstructural analysis

Scan electron microscope (SEM) test is generally used for the microstructural analysis of concrete. The SEM test provides high-resolution images with high levels of magnification. The SEM test assesses the failure mechanism. Precipitation of calcite in concrete and mortar was analyzed by scanning electron microscopy. Bacteria that were rod-shaped and linked with crystals of calcite were observed. Because of the dismissal, the concrete's imperviousness is enhanced as the dismissal behaves as a hurdle to detrimental

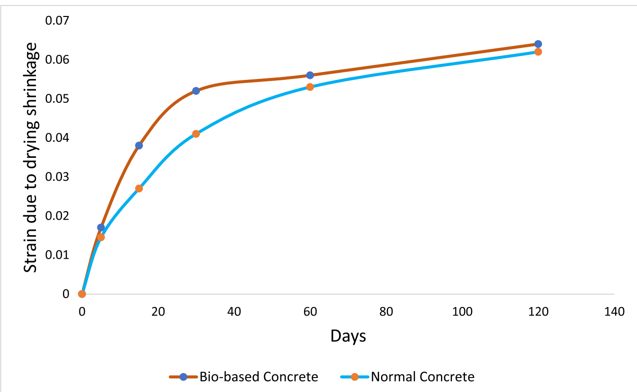

Fig. 8. Drying shrinkage of bio-based concrete with Bacillus Licheniformis and Bacillus Sphaericus vs. normal concrete.
Data from Reference [133].

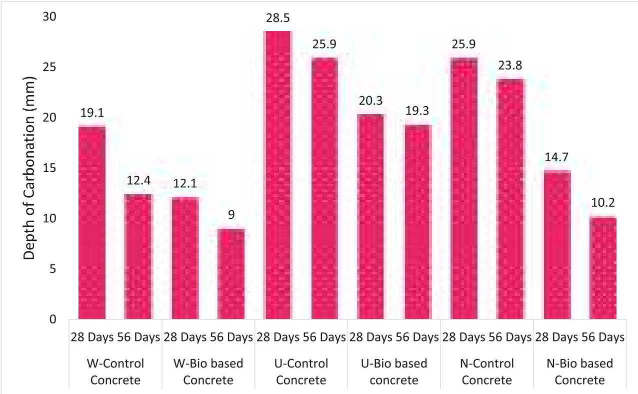

Fig. 9. Depth of carbonation for normal and bio-based concrete.
Data from Reference [118].

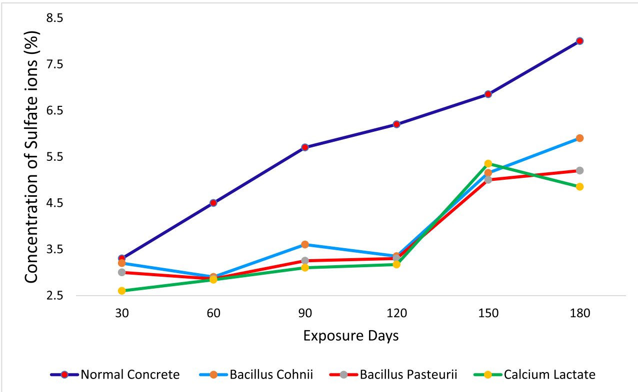

Fig. 10. Test outcome sulfate resistance on normal and bio-based concrete.
Data from reference [118].

elements as those materials infiltrate that specimen [88]. Including a bacterial agent in the specimen could improve the micro-structural behavior of the specimen by precipitation of minerals. This has also been confirmed by scanning electron microscopic analysis, electron dispersive spectra, and x-ray diffraction study. The author specified that the inclusion of 28×10^5 cfu/millimeter BM bacterial agent had 39% more weight of calcium in comparison with another amount of bacterial agent and without a bacterial agent in the specimen [61]. The scanning electron microscopic spectra displayed embedded crystals of calcite with a bacterial agent. It was noted that the calcite existed in the shape of $CaCO_3$ as higher proportions of calcium were present in the specimen [141]. This was also established by utilizing electron dispersive x-ray and x-ray diffraction spectra. It could enhance the concrete's durability [142,143]. Fig. 11 displays the scanning electron microscopy micrographs of the reference sample and bacteria-based concrete [31]. The strength of rice husk ash-based concrete was enhanced by including bacterial agents because of the dismissal of $CaCO_3$ in pores. This was established by utilizing scanning electron microscopic micrographs. Fig. 12 displays the scanning electron microscopy micrographs of the reference sample and bacterial rice husk ash-based concrete. It can be observed that the calcite in the bacteria-based concrete assisted in filling the pores and voids [31]. As per Siddique et al. [101], the development of crystals of calcium-hydrate is low, and the gel of calcium-silicate-hydrate is highly consistent and thickly dispersed in bio-based concrete's micro-structure in comparison to normal concrete. This approves the test outcomes conferred in strength characteristics that microstructure densification happens in bio-based concrete, instigating a lowered pore size and enhanced strength in concrete [144]. The result established the deposition of $CaCO_3$ within the cracking of test specimens attained utilizing micro-structures. Hence with the rise in the signal transmission rate of UPV, the acid resistance, water absorption, and permeability against chloride ions are also reduced [34,64].

9. Challenges related to bio-based concrete

Regardless of the different possibilities of using bio-based concrete for self-healing purposes, adding bio-cells in a primarily alkaline environment of numerous materials could be challenging. It is projected that bio-based concrete is generally (1200 USD / kg) without transporting, preserving, and safeguarding the cells [136]. Nevertheless, the challenge of employing bio-based concrete relates to budget issues, sustainability, and atmospheric insinuations. Little research has been performed on using bacteria in concrete over the

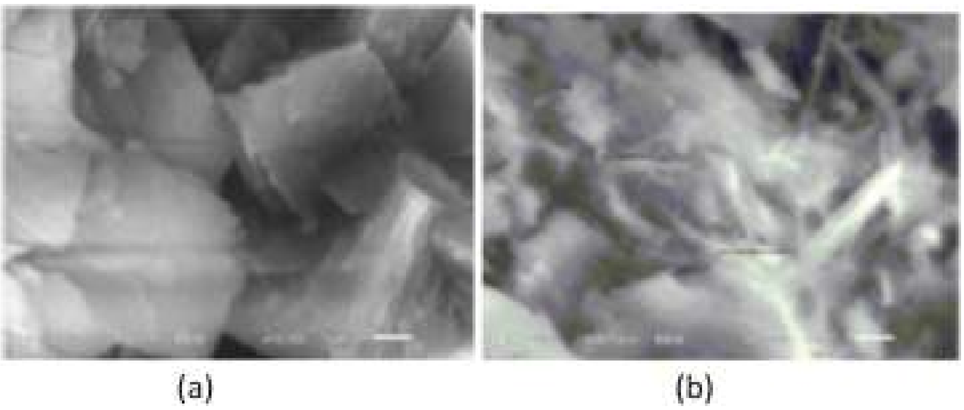

Fig. 11. Scan electron microscope images (a) Reference sample (b) Calcite precipitation of bacteria in 10% fly ash.
(b) Used as per permission from Elsevier [33].

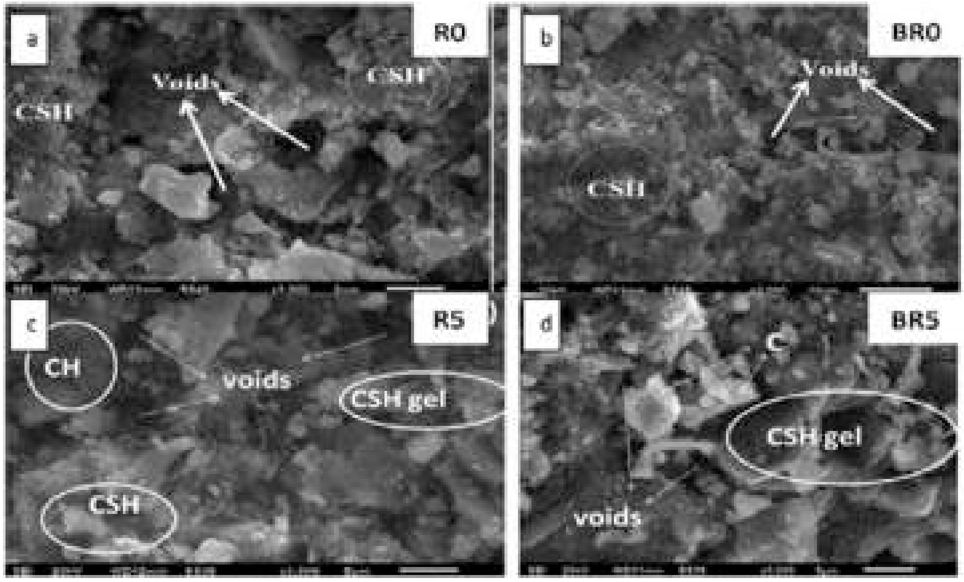

Fig. 12. Scan electron microscope images (a) Reference concrete, (b) bacteria-based concrete, (c) concrete with rice husk ash, (d) bacteria-based concrete with rice husk ash.
(d) Used as per permission from Elsevier [33].

life cycle analysis method (LCA) [145,146]. The outcome of these studies could summarize the atmospheric insinuations of the utilization of bacterial material in concrete. Another challenge related to bio-based self-healing concrete is the vast knowledge gap. As per the author's suggestion, there should be a faculty position in bio-based cementitious composites about the strength and durability of reinforced concrete structures in every major university. Moreover, the curriculum of concrete subjects should be integrated with the durability, corrosion, and reliability of bio-based self-healing concrete at Bachelor's and Master's levels, which is currently very rare in the current situation [147]; it will ensure that coming generations of civil engineering students will receive up to date knowledge about the current issues and problems related to bio-based concrete. Calcium carbonate, formed in the cracks of SHC, mostly closes the cracks but rarely recovers the reduction in strength. It is also mandatory to offer the basic scientific foundation essential to overcome technological hurdles, for instance, questions related to novel binding materials to be utilized in different cementitious composites.

Moreover, because $CaCO_3$ is resolved in low pH levels, it will not offer a long-term sealing effect to the cracks when the concrete is exposed to high pH levels. Also, $CaCO_3$ is very brittle, making the SHC unsuitable in the longer term, leading to fractures under load and cracks opening. The adhesion of $CaCO_3$, which has been placed to the concrete's fractured surface, is one of the highly significant factors in evaluating the efficiency of the self-healing system. As a result, it requires a comprehensive assessment of the adhesion behavior of $CaCO_3$ in the concrete's matrix. In the construction industry, cement formation is usually highly responsible for the outflow of greenhouse gases, which estimates up to 7 of the total formation of carbon dioxide yearly [148]. Different research has been performed recently to decrease cement's environmental effect. Though targeting cement replacement could be challenging, the possible atmospheric impact study and utilized method to reduce the atmospheric effect could offer awareness on decreasing the outflow of greenhouse gases through the bacterial material as a binder. Table 9 summarizes the projected carbon dioxide production for making 1 ton of bio-based concrete with reference to [145]. As observed from Table 9, the low to higher estimates for yeast and urea are relatively high, which contributes to the ambiguity related to the exercise of bacterial concrete, which necessitates further research in this domain.

10. Future of utilizing bacterial materials in concrete

Before presenting this notion, it must be demonstrated on a commercial level. Also, the issue of optimization of the proportion of nutrients is required to be given consideration. Carbonation characteristics, shrinkage, and corrosion of concrete are yet to be examined thoroughly. A detailed examination of previous characteristics will illuminate the actual act of bio-based SHC. Though this idea has displayed good outcomes in the laboratory, its effectiveness in caring for significant concrete members is required to be further tested under high temperatures and salty environments. Estimation of real service life could only be attained with the help of detailed expertise on the effectiveness of SH, and this is the solution to endorsing this idea between owners and contractors. Additionally, the applying procedures and applications, the long-term impact of bacterial material, and the durability of bio-modified calcium carbonate have not been explored in detail. More studies and research in this domain are recommended to enhance the potential of applying bio-based materials in self-healing concrete. Most of the procedures of autogenous healing are capable of repairing cracks up to 150 μm. Also, the technology of autonomous healing can repair large cracks (up to 1 mm) and generally acts fast. The combination of these novel technologies may endorse the development of SHC, for instance, geopolymer concrete [149–151], nano-modified concrete [152–155], organic [156,157], and self-assembly technology in concrete.

11. Conclusion

The significance of this study is to comprehend the utilization of urea-developing bacterial isolate, for instance, bacillus Pasteurii species, in healing concrete cracks. The present work has reviewed several kinds of bacterial materials that could be utilized to heal cracks.

- The present work has also suggested that bacterial agents positively impact Portland cement's concrete and mortar compression strength.
- The healing of cracks in bio-based concrete relies on the accessibility of nutrients and the persistence of bacterial living cells. Past research also used this method; it needs a particular method to reserve the live cells, which stances a big challenge for its application in large-scale bio-based self-healing concrete.
- The advantage of utilizing a bacterial agent is that it reduces water infiltration and chloride ions' permeability.
- The inclusion of bio-based material is observed to enhance bio-concrete's strength and durability characteristics. This could be because of a decreased pore system and improved densification in the concrete's matrix, further reducing the possibility of penetrating acids and chemicals in concrete.
- Among different curing methods, such as calcium chloride-urea, immersion in water, steam method, and calcium-lactate-urea, water curing was observed to be most effective in all of them.
- Past research has observed that bio-based concrete frequently shows high resistance against carbonation, chloride, and sulfate compared to normal concrete. A high dry shrinkage in bio-based concrete was observed.
- Considering challenges related to environmental and monetary issues, bio-based concrete had a high cost of application, which is paramount because of its cultivation, transport, and preservation of the bacteria's living cells and nutrients.
- From the LCA study, the formation of urea, specifically during the synthesis of ammonia, is energy demanding method and causes the outflow of NO gas, which could cause considerable different impact values in association with changes in climate, atmosphere, and environment related to the production of carbon dioxide

The outcomes of the present work suggest that utilizing microbial materials in concrete could be a substitute and sealant for high-

Table 9
Outcome of LCA for making 1 ton of bio-based concrete on the effect of the environment (data from reference[145]).

Material required	The projected amount required (kg)	Highest estimate (kg CO_2 -eq)	Lower estimate (kg CO_2 -eq)
Fine aggregate	845	3.15	3.13
Urea	0.31–1	1.55	0.45
Yeast	0.028–0.068	0.18	0.03
Salt	0.15–0.24	0.025	0.015
Limestone	145	6.51	2.55
Electricity	4.5 kWh	2.5	0.2
Glucose	1–2.5	1.03	0.45
Peptone	0.1–0.22	–	–
Production of bio-based concrete	–	9.9	5.0
Total	1 ton	24.5	11.5

quality concrete, which is very cost-efficient and sustainable and ultimately leads to advancing the construction material's durability. Comparative research in this domain could better understand the identifications of highly appropriate procedures for including bio-based material into concrete with cracking.

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Data Availability

Data is accessible by request from the conforming author.

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