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Bio-Based approach of Self-Healing Concrete: A Comprehensive Review

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Abstract:

In concrete buildings, microcrack development is an inevitable occurrence. Due to the infiltration of water carrying unwanted elements into the concrete material, this occurrence has the potential to reduce the strength and service life of these structures. Thus, concrete restoration is required before the cracks become larger and cause more damage. Self-healing concrete made of biological materials might be a good way to reduce this risk. This technology for self-healing concrete is brand-new. The use of bio-based self-healing concrete on a bigger scale in structures will require additional study and reviews, despite the fact that some have already been conducted in this area. These are necessary to gather highly specific thoughts about the methods, prospects, and issues of this material. In this review, we'll focus on a few key aspects of bio-based self-healing concrete, including: (1) various approaches of bio-based techniques; (2) necessary time and conditions; (3) repeatability of healing approaches; (4) comparison between the potential of this innovative material with traditional concrete; (5) effects on materials after healing; and (6) existing research gaps and future recommendations. Overall, the study offers useful details regarding several kinds of self-healing concrete and an assessment of how well it performs when used in various real-world situations.

Keywords: *Concrete; Bio-based self-healing; Crack width; Water permeability; Curing age.*

1 Introduction:

According to the American Concrete Institute (ACI) concrete is a composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregates, the binder is a mixture of a Portland cement and water, with or without admixtures. It is estimated that about 30 million tons of concrete are produced and consumed each year(Seifan et al., 2018). Concrete can crack due to plastic shrinkage, thermal stresses, settling, drying shrinkage, weathering, corrosion of steel, or due to application of load(Souradeep & Kua, 2016). An analysis done by Diane Gardner et al. shown in Figure1 directly indicates that cracking involves structural damage at an enormous scale, while damage involves repair, maintenance and replacement of existing structures. In the UK 35–45% and in EU 50% of infrastructure budget is being utilized for damage repairing and maintenance of old and new structures(Gardner et al., 2018). Figure 2 shows the consequences of maintenance operations of concrete structures. Self-healing or autonomous repair is an effective method of sealing damaging fissures which is preferred nowadays by researchers to minimize the drawbacks of cracking in concrete strictures(Danish et al., 2020). The major benefits of self-healing concrete rather than repairing and replacement of structures are visualized in Figure 3. In recent years the research interest in self-healing concrete specially bio-based healing has been increased noticeably. Aerobic and anaerobic micro-organisms such as bacteria and fungi are being utilized as self-healing agents in bio-based concrete. Bacterial self-healing involves the precipitation of calcium carbonate in cracks caused by the direct action of bacterium species such as Bacillus Subtilis on calcium compounds such as calcium lactate or by urea breakdown by ureolytic bacteria such as Bacillus Sphaericus (Gupta et al., 2017). Though $CaCO_3$ is the most appropriate concrete filler, some issues have been noticed in bacteria induced concrete in detrimental environment such as high pH values, small pores, severe moisture deficiency, fluctuating temperatures, and low availability of nutrients(Menon et al., 2019). Since researchers proceeds to further investigation on other micro-organisms including fungi along with bacteria. In this review, self-healing approaches, required time and conditions, properties, benefits over traditional concrete and present research gaps of bio-based self-healing concrete have been discussed.

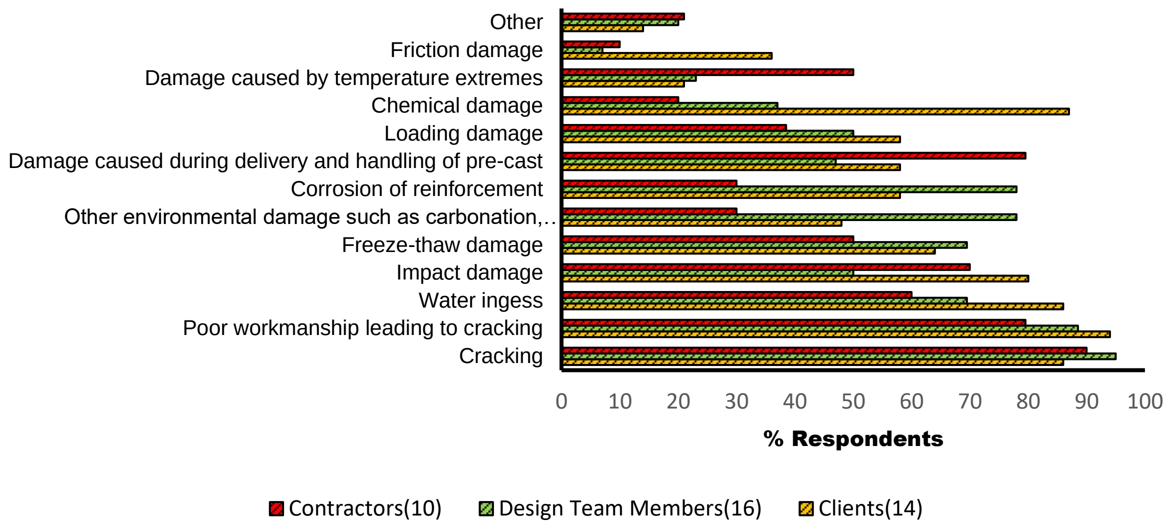

Figure 1. The main causes of damage in concrete structures(Gardner et al., 2018)

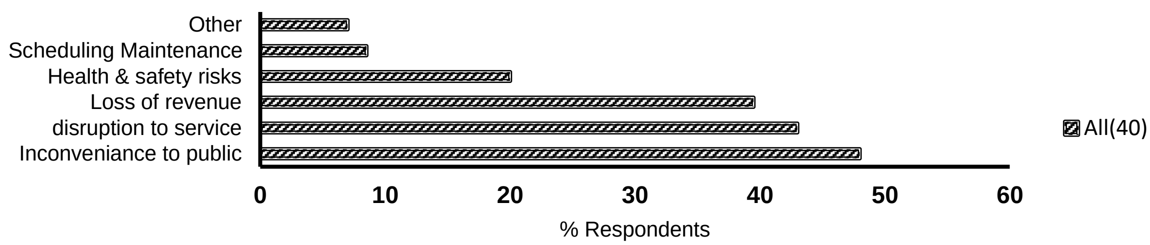

Figure 2. The consequential effects of maintenance(Gardner et al., 2018)

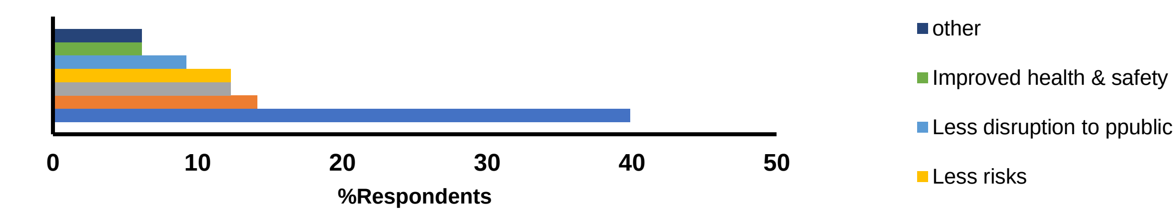

Figure 3. Benefits of self-healing concrete to justify paying a premium for the material(Danish et al., 2020).

2 Various approaches of bio-based concrete

Several approaches of bio-based self-healing concrete that have been found are summarized in Figure 4 below.

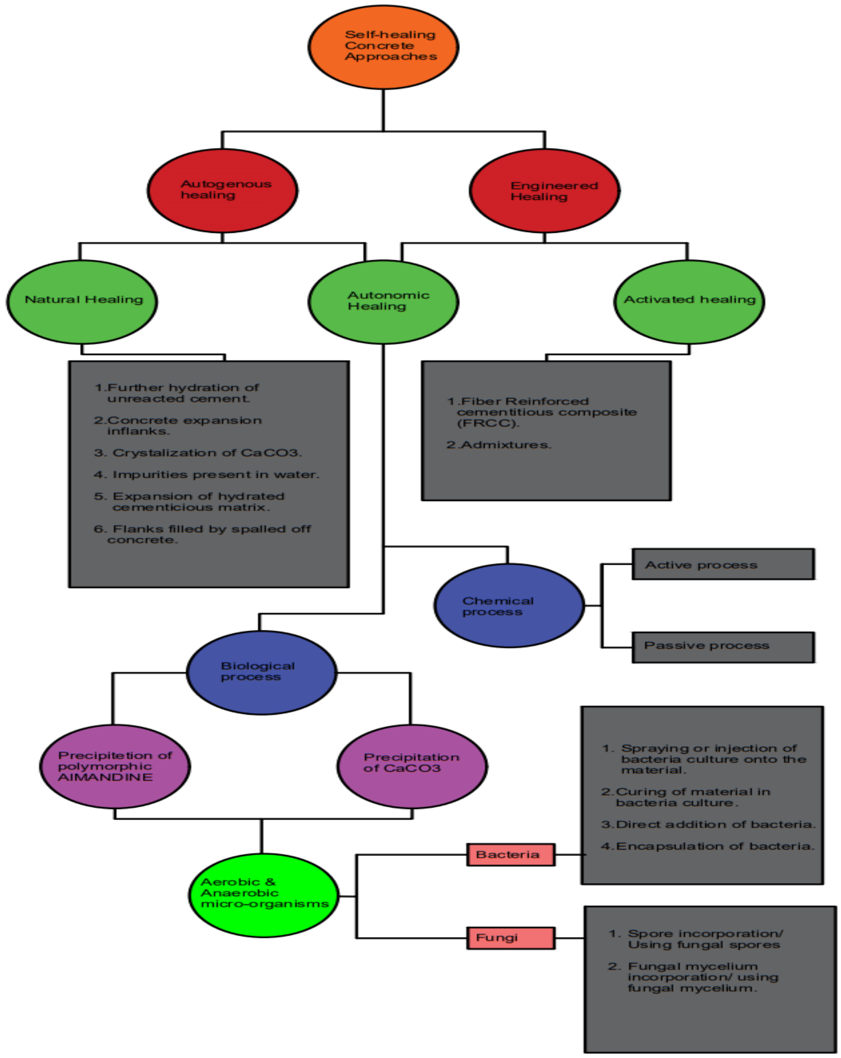

Figure 4. Approach tree of self-healing concrete (Danish et al., 2020, Gupta et al., 2017, Konwarh et al., 2020)

3 Necessary time and conditions

Crack healing efficiency of bacteria based self-healing concretes varies due to healing condition, cracking age and crack width(Luo et al., 2015). Several researchers found that the healing efficiency of bacteria based concrete decreases with increasing crack width(Luo et al., 2015)(Menon et al., 2019). In Table 1 the crack repairing efficiency of different crack width has been described. In Figure 5 & 6 the area repair rate of self-healing concrete at different cracking age and different curing conditions with respect to time has been visualized.

Table 1. Percentage of crack repair of different crack width

Crack width (mm)	Crack repair	Days	Healing quantification	Reference
0.1-0.3	85%	20	80% after 14 days curing	(Luo et al., 2015)
0.3-0.5	50%-70%	20		
Up to 8	<30%	20	43% after 28 days curing	
0.273	86%	28	86% after 28 days	(Hu et al., 2018)

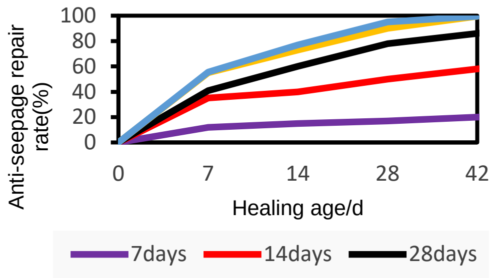

Figure 5. Area repair rate of self-healing concrete at different cracking age(Luo et al., 2015)

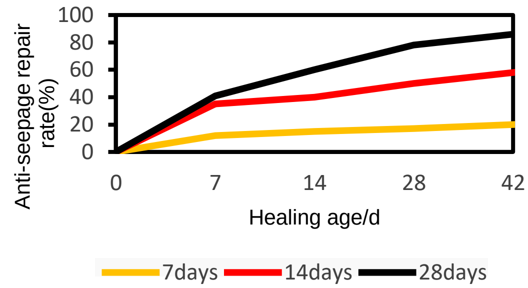

Figure 6. Area repair rate of self-healing concrete for different curing ways(Luo et al., 2015)

4 Effects on concrete material after healing

Microbial agents affect concrete's durability, strength and water permeability. Table 2 describes the effects of healing agents on properties of concrete material.

Table 2. Effect of microbial agent on compressive strength and water absorption(Danish et al., 2020)

Micro-organisms	*Bacillus sphaericus*	*S. pasteurii*	*Bacillus cohnii*	*Bacillus pseudofirmus*	*Diaphorobacter nitroreducens*
Compressive strength	increases	increases	increases	decreases	decreases
Water absorption	decreases	decreases	_	_	_
Permeability	decreases	_	_	_	_

5 Repeatability of healing approaches

All existing self-healing mechanisms are "feasible" to varying degrees, but each mechanism in a sustainable infrastructure must also be "robust". At least six robustness requirements, including shelf life, pervasiveness, quality, reliability, versatility, and repeatability, must be met by a healing mechanism to be considered robust.(Li & Herbert, 2012). Of these six requirements, the repeatability requirement poses the greatest challenge to healing processes because certain external stresses will inevitably be repeated over the life of infrastructure, leading to repeated cracking. However, a detailed investigation of the repeatability of enhanced autogenous self-healing in ECC by Sahmaran (Şahmaran et al., 2015) showed that the healing mechanism in the presence of water can still provide satisfactory results after nine cycles of loading and unloading. According to V. Li(Li & Herbert, 2012), the enhanced autogenous healing of rigid foam is reproducible in the natural environment but is highly dependent on the degree of damage and environmental condition.

6 Comparison between the potential of this innovative material with traditional concrete:

The most significant property of concrete are durability and compressive strength. In Table 3 the compressive strength of traditional concrete & bio-based self-healing has been compared.

Table 3. Comparison of compressive strength of conventional concrete and bacterial concrete (Luhar & Gourav, 2015)

No. of days	Compressive strength of conventional concrete cubes, N/mm2	Compressive strength of B.sphaericus concrete cubes, N/mm2	% increase in Strength
3	19.24	25.16	30.76
7	23.66	34.58	46.15
28	34.52	45.72	32.21

Additionally, the impermeability of self-healing concrete is higher than traditional concrete(Danish et al., 2020). Microbial-induced self-healing is environmentally beneficial as it helps to reduce Carbon emission in cement manufacturing (Jonkers et al., 2010). It also reduces corrosion and pollution of water by decreasing industrial byproducts.

7 Conclusion including current research gap and recommendations:

The potential of bio-based technology to self-heal cracks without human intervention is one of its key features. The bio-based approach is also sustainable and environmentally friendly. The bio-based method reduces maintenance requirements, increases the service life of concrete structures, and reduces the environmental impact of concrete production and maintenance by enabling self-healing.

(i) According to the study of (Li & Herbert, 2012) five self-healing approaches mentioned are chemical encapsulation, bacterial encapsulation, mineral admixtures, chemical in glass tubing, and intrinsic healing with self-controlled tight crack width. Here the approaches can be combined to investigate the results of further enhancement in self-healing.
(ii) Large number of specimens needed to stabilize or evaluate the results found (Jonkers et al., 2010).

(iii)The most common curing conditions that the researchers looked into were being exposed to the local climate, being submerged in water, using freeze-thaw and wet-dry cycles, and maintaining a controlled temperature and relative humidity. The beneficial self-healing mechanism can be adopted by acquiring more in-depth knowledge of the surrounding environment and its effects on self-healing. (Yıldırım et al., 2018).

(iv) The corrosion-induced physical and chemical reactions that can alter the self-healing process, as well as the plastic deformation of steel that results in concrete deformations that are permanent. A thorough investigation into the effects of corrosion on each of the healing methods and the efficacy of employed methods in the event of sustained cracks is required to fill the aforementioned research gaps. (Keskin et al., 2016).

(v) Repeating nature of different external loads causes repeating cracking. A robust healing method is required but multiple crack over lifetime of the structure hindrances. The effect of high ratio of self-healing agent and cost relationship is still a concern for users and manufacturers. (Khaliq & Ehsan, 2016)

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