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Review

Autonomous healing in concrete by bio-based healing agents – A review

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HIGHLIGHTS

- Effectiveness of self-healing by bacteria in concrete is discussed.
- Encapsulation techniques and materials for bio-based healing action is presented.
- Six robustness factors for effective healing by bacteria in concrete are highlighted and discussed.
- Assessment methods for bio-based self-healing are discussed and compared.

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ABSTRACT

Crack formation in concrete structures is inevitable due to deterioration throughout its service life due to various load and non-load factors. Therefore, repair and maintenance operations are needed to prevent cracks from propagating and decrease the structures' service life. However, accessibility to cracked zone may be difficult; besides such operations require capital and labor and contribute to pollution due to anthropogenic activities and usage of more repair materials. Self-healing may be a possible solution to reduce manual intervention. Autonomous crack sealing by bacteria induced carbonate precipitation is an environmental friendly mechanism which is studied intensively by many researchers worldwide. This review focuses on evaluation of crack healing by bacteria when it is added directly to the concrete or added after encapsulating it into a protective shell. Four key aspects that determine effectiveness of bacterial self- healing have been highlighted and discussed; they are capsule material and encapsulation of bio-agents, survival of capsules during concrete mixing, effect of addition of bio-agents or capsules on concrete properties, and sealing ability and recovery of mechanical and durability properties. Finally, research gaps and scope of future research work are identified and discussed.

Contents

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1. Introduction

Cracking is inevitable in concrete due to its relatively lower tensile strength and action of different load and non-load factors. Sources of cracking may be varied including plastic shrinkage, drying shrinkage, thermal stresses, external loading and rebar corrosion or coupled effect of multiple factors. For example, microcracks may form due to shrinkage but may propagate at a lower stress level when external loading is applied causing network of cracks. Such network of cracks gives easy access to moisture and chemicals to seep into the structure or degrade concrete chemically. Such problems are worse in the tropics due to higher moisture content in the air and high precipitation. Cracks can be manually repaired but there are several problems associated with manual maintenance and repair operations such as impact on environment, accessibility and cost. Different chemical and cement based repair materials are used presently. Cement production is associated with about 7% of global anthropogenic CO_2 emission [1] while chemical healing agents present threats including material incompatibility, health and environmental hazards [2]. Microcracks may originate in concrete just after construction or at advanced stage which is often unnoticed until it leads to major durability or structural issues. It is also a financial burden to carry out routine repair operations on facilities. Therefore, there is a need to find a sustainable way of healing cracks which involve less cost and eliminate the need of manual intervention.

Self-healing is an emerging concept of delivering high quality materials combined with the capability to heal damages and it has received much attention in past decade for application in building structures. Therefore, an effective self-healing mechanism may be able to reduce repair and maintenance works substantially and concomitant environmental and economic impacts. Recently, a sustainable mechanism of self-healing using microbial induced precipitation of calcium carbonate has been intensively studied to seal and heal cracks. Self-healing by microbes involve precipitation of calcium carbonate in cracks by direct action of bacteria species including Bacillus Subtilis on calcium compound such as calcium lactate [3] or by decomposition of urea by ureolytic bacteria such as Bacillus Sphaericus [4,5]. Calcium carbonate precipitation by microbes is compatible with concrete and the process of formation is environmentally friendly [6]. Bacillus Sphaericus is known to be harmless to human [7]. Additionally, during the process oxygen is consumed and therefore it also reduces the chance of reinforcement corrosion. The genre Bacillus has qualities including tolerance to high alkaline environment and moisture and capacity to form spores which make it suitable to use as self-healing agent in concrete. Therefore, Bacillus has been most commonly used in research studies as the bio-agent for calcite precipitation [3–5,8–10].

The review aims at evaluation of self-healing in concrete by biological action when the bacteria are directly added to concrete or added after encapsulation in mineral or chemical compounds. The discussion is conducted in the light of several key criteria including capsule material and encapsulation of bio-agents, survival of capsules during concrete mixing, viability of bacteria, effect of addition of bio-agents or capsules on concrete properties, and sealing ability and recovery of mechanical and durability properties.

2. Bio-based self-healing-mechanisms and approaches

Mentioned by Hammes and Verstraete [11], precipitation of calcium carbonate in natural environment is ideally influenced by concentration of calcium ions, pH of the solution, concentration of dissolved inorganic carbon and availability of nucleation sites. While the first three conditions relate to concrete matrix, the fourth one is provided by the bacterial cell itself. Bacterial precipitation may be achieved through different pathways like conversion of calcium compound such as Ca-lactate or hydrolysis of urea by (ureolytic) bacterial metabolism. In the first mechanism, crack openings let oxygen penetrate inside concrete and bacteria along cracked surfaces convert calcium lactate into calcium carbonate and carbon dioxide. If there are portlandite particles in the vicinity reaction with produced carbon dioxide would yield more calcium carbonate which may as well be used for healing. Therefore, it may be understood that this mechanism would be more efficient in case of fresh concrete when there are still unhydrated calcium hydroxide particles. The second pathway is precipitation of calcium carbonate through hydrolysis of urea into ammonium and carbonate. Bacteria Bacillus Sphaericus produce enzyme urease which act as a catalyst in the process. Negatively charged bacterial cell draws calcium ion from a calcium source such as calcium nitrate to react with the produced carbonate to precipitate calcium carbonate.

Therefore, in a nutshell, self-healing by bacteria may be accomplished by any of these mechanisms but the efficiency of healing in concrete would depend on a number of other factors including availability of moisture, crack area or width to be healed, age of concrete and survival of bacteria in long term.

2.1. Healing by direct addition of bio-agents to concrete

Jonkers and Schalngen [12] tested the feasibility of application of bacteria spores for development of self-healing concrete. Three species of bacteria mixed in cement stone were tested – Bacillus cohnii, Bacillus halodurans and Bacillus pseudofirmus. Cement stone chips were cured in yeast extract and peptone based medium and then tested for compressive and tensile strength. There was no significant difference between bacteria containing samples and control samples. Scanning electron microscope (SEM) images showed precipitation of calcium carbonate crystals after 12 days of incubation. However, in this preliminary research the organic carbon sources or food for bacteria were externally supplied and germination was observed once samples were cured in the medium. Possible effect of addition of yeast extract and peptone along with mineral precursor compound was carried out in a later study by Jonkers et al. [8]. For self-healing action to be accomplished, the primary challenge is the survival of bacteria in highly alkaline environment of concrete. Jonkers et al. [8] investigated the potential of carbonate precipitation by species of bacteria which can remain viable while being added directly to concrete. Two species of spore forming alkaliphilic bacteria - Bacillus pseudofirmus and Bacillus cohnii were tested. Calcium acetate and calcium lactate were tested as mineral precursor compound. It was observed that only calcium lactate did not affect strength and resulted in slight increase of strength. 20–80 μm sized calcium carbonate crystals were observed on specimens but the precipitate was observed only