Methods and Limitations for Self-Healing of Concrete and Possibility of Post Fire Self- Healing – A Review

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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. Concrete is being extensively used in construction industry worldwide because of its avail-ability and affordability but it is vulnerable to crack formation. Because of cracking concrete's durability reduces due to ingression of chloride and water which corrodes rebars in rein-forced concrete. 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. Therefore, self-healing techniques are known methods to cease cracking and regaining the strength and durability of concrete. 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 and available self-healing approaches considering various healing materials with respect to performance and application.

CONTENTS

1. INTRODUCTION

In the construction industries fast declination of concrete structure being a major setback necessitates additional improvement. The implementation of bio concrete enhances the service life of concrete structures, reduces repair and maintenance costs and thus leads to decrease of new construction works which also reduces the utilization of raw materials, savage in energy consumption. This finally results to decelerate carbon dioxide emissions due to cement plant into atmosphere. 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. Early micro-cracks are extremely difficult to be detected in the cementitious matrix due to their size; however, from external exposure to environmental condition and loadings (cyclic or static) the micro-size crack leads to the formation of macro-size cracks. Figure 1 [17]. Therefore, an effective self-healing mechanism may be able to reduce repair and maintenance works substantially and concomitant environmental and economic impacts [12]. The computation and characterization of self-healing products can be done by ultrasonic pulse velocity values. This test was done by passing mechanically induced pulses by transducers in the frequency ranges from 20 to 150/s through concrete. The waves can be passed by various types of transmission i.e. direct transmission, surface transmission and semi-direct transmission. The waves are passed through the concrete samples by direct transmission from 7, 14 and 28 days after cracking. There is an increase in velocities with increase in time period showing the improvement in impermeable nature of concrete indicating the decrease in crack width by calcium carbonate formation [8]. Mohammed et al investigates Bio logical self-healing process as a promising technique to address the concerns associated with concrete corrosion problems. Two compositions of concrete samples were prepared and casted – CEMI and CEMIII with 60% of Ground Granulated Blast Furnace Slag (GGBS) with and without bio product. Bacteria spores at different concentrations were directly added into the fresh concrete mixture to determine the best possible combinations without sacrificing concrete properties. A Shewanella like strain was chosen as a biological candidate as it is a facultative bacterium meaning it can grow in the presence and absence of O2. The last point is valuable as the strain is easy to handle inside and outside the concrete. It also thrives in versatile habitats and it is known to reduce a variety of metals, including iron. Bacteria spores at different concentrations were directly added into the fresh concrete mixture to determine the best possible combinations without sacrificing concrete properties. To assess the effectiveness of the self-healing concrete the following tests carried out such as, compressive strength, water absorption via capillary, open porosity test, growing bacteria evolution analysis, Scanning electron microscope (SEM) [16]. Self-healing in concrete is of two types; autogenous healing and autonomous healing. When cracks are produced, some of them with smaller widths, are closed as a result of autogenous healing. The phenomenon of autogenous healing involves two processes (i) formation of calcium carbonate ($CaCO_3$) crystals directly from calcium ions (Ca^{2+}) in cement and carbonate ions (CO_3^{2-}) present in water and (ii) continued hydration of anhydrous cement particles or some pozzolan when cracks are exposed to humid conditions . As a result, $CaCO_3$ is formed, which acts as a crack healing product in self-healing concrete [5].

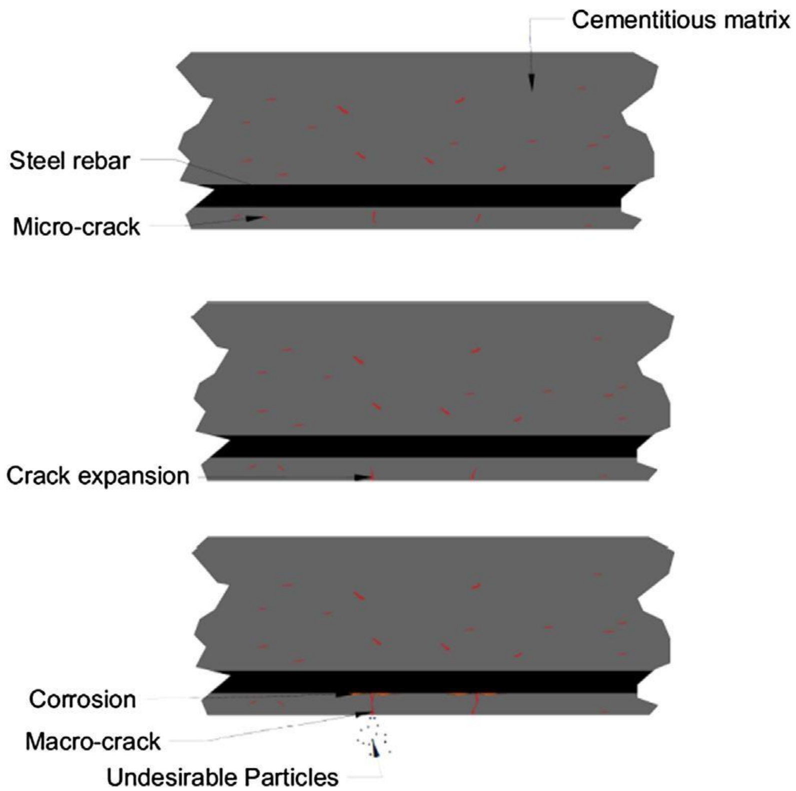

Figure 1- Crack formation progress in cementitious matrix.

Concrete may be deteriorated by several ways and several structures may be affected by this deterioration. Figure 2& 3 explains it [10]. Cracking is one of the important causes of concrete deterioration and reduction in durability [10] as Fig. 2&3 shows that cracking is one of the main cause of structure damage/deterioration reported by clients, designers and contractors. Cracks formed in concrete can be categorize into following states:

(i) Plastic state

a. Plastic settlement

b. Formwork movement

c. Plastic shrinkage

(ii) Hardened state

a. Thermal stress

b. Chemical reaction

c. Error in detailing and design

d. External/overload

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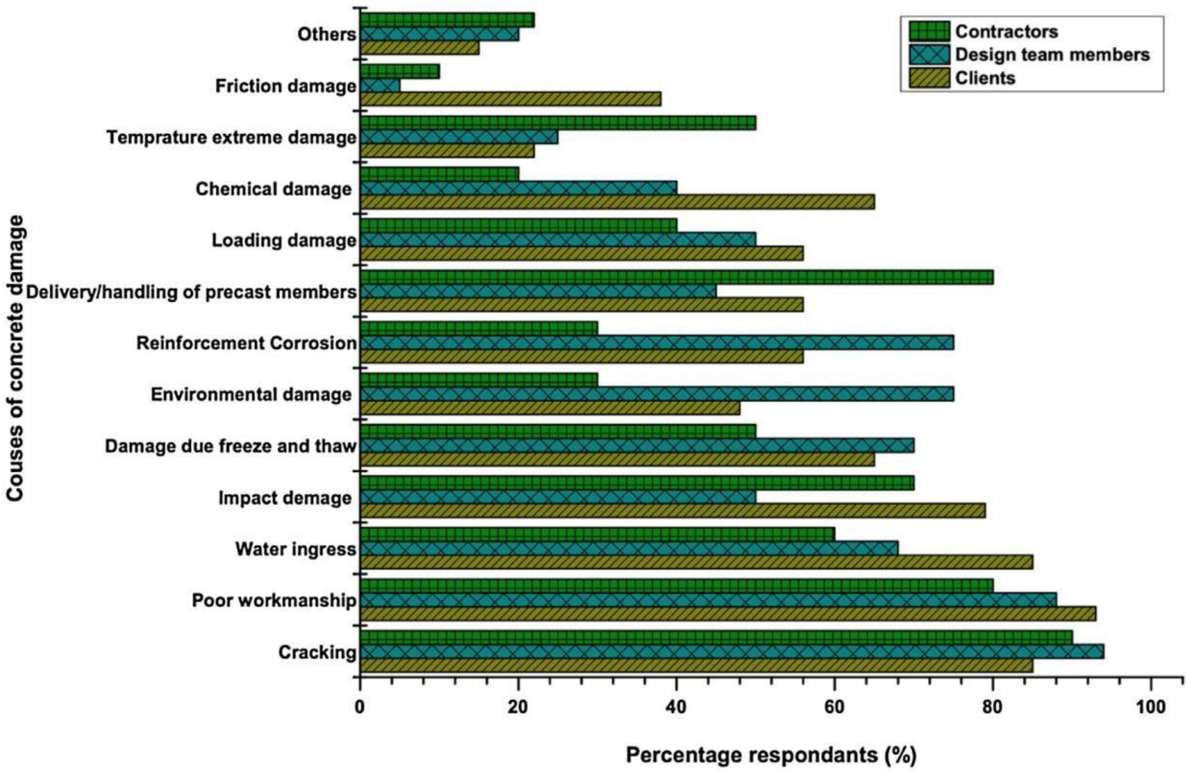

Figure 2 - Significant causes of deterioration/damage of concrete structures

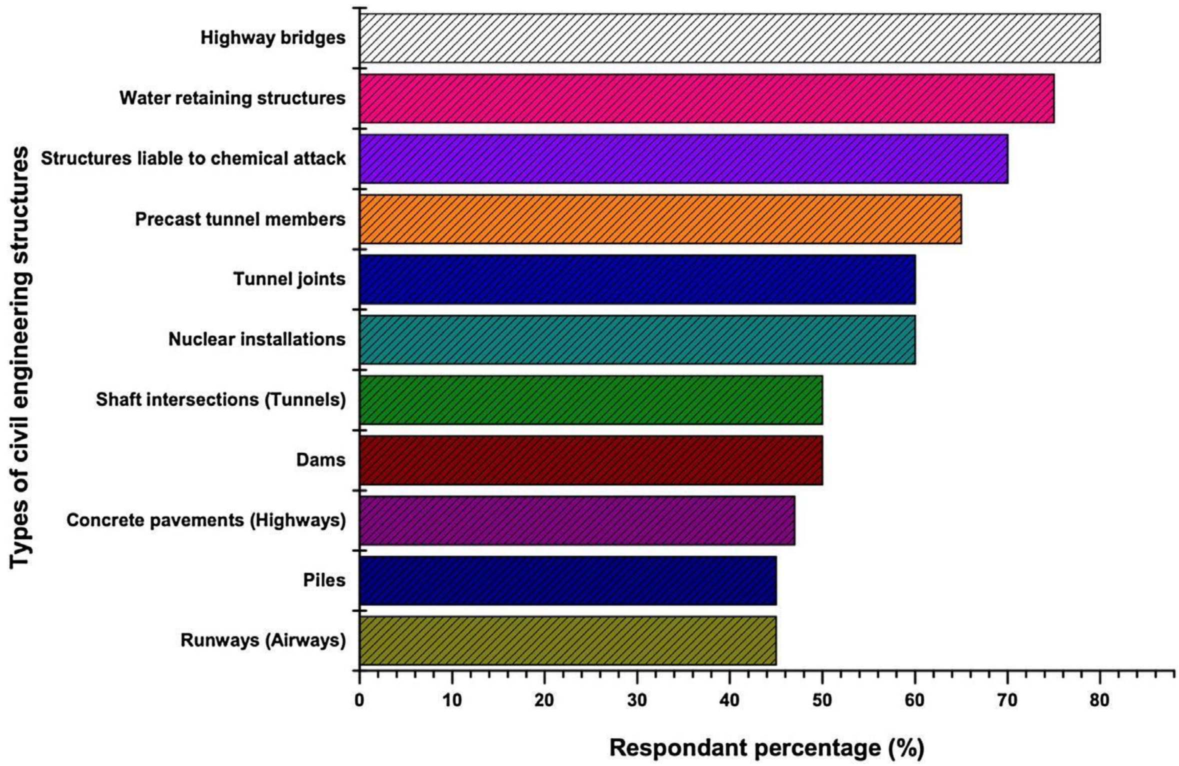

Figure 3 -Application of self-healing in different civil engineering structures

2. Methodologies for self-healing of concrete

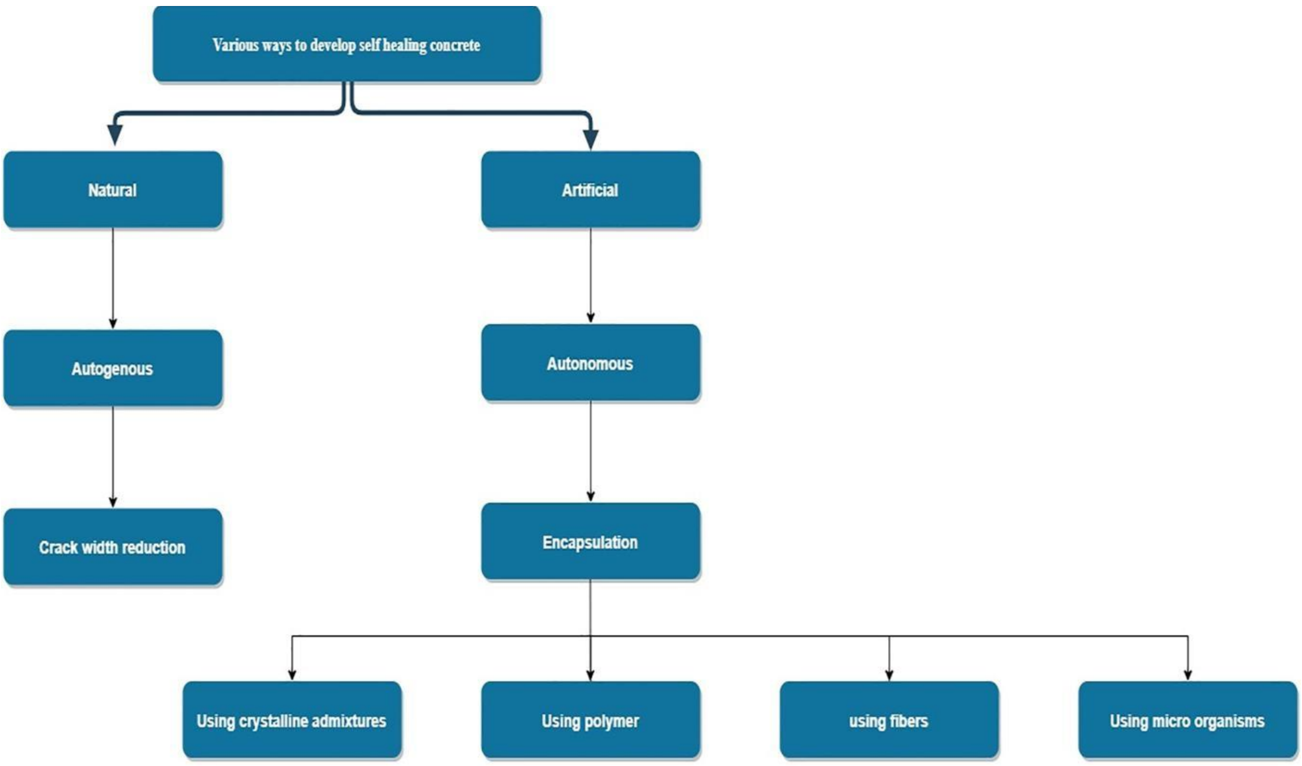

Fig. 4. Flowchart on various ways to develop self-healing concrete.

2.1. Rehydration

Survivability of bacteria is very important. However, when bio-agents are directly added to concrete there may be several barriers to survivability of bacteria. Jonkers noted that even though bacteria spores were added lifetime of the unprotected spores was limited to only two month and therefore effective self-healing was observed only in young samples. There may be several reasons for this including alkalinity of cement matrix, mixing of concrete and hydration of cement. Activity may be substantially decreased when spores are exposed to high alkalin environment over long time. Moreover, during mixing some spores may be damaged due to mixing force or impact of aggregates. Hydration of cement reduces porosity and pore size of matrix over time to as much as 0.5 mm while bacteria cells are typically bigger than such size. Therefore, with shrinkage of pores germination of cells may be drastically reduced or stopped at late stage of a concrete structure. One way to overcome this limitation is to encapsulate the bacteria to protect them without affecting any of concrete properties and carbonate precipitation by bacteria [12]. Hydration process of self-healing is the occurrence of crack healing on materials due to the hydration of un-hydrated cementitious particles remained in the matrix white crystalline layers formed over the cracks due to carbonation between calcium hydroxide from concrete and exposure to the

Atmosphere or reactions between calcium hydrogen from water and calcium hydroxide from concrete [17].

2.2. Bacterial

2.2.1 Bacterial spores' powder

Wu et al employed cementitious materials produced by calcium carbide slag, fly ash, desulfurized gypsum and sodium silicate hydration reaction as wall material and yeast powder and bacterial spores' powder as core material to prepare bio capsule for the self- healing of concrete crack. The cementitious material have strength and they are highly compatible with concrete. Wu et al used bacterial spores' powder and mixture of core material substance to obtain lumpy mixture. Bio capsule core material pallets of a consistent size were prepared by lumpy mixture by adding lumpy mixture into a multipurpose palletizer to perform pressing, extruding, pelleting followed by rolling, drying and sieving [1]. Stuckrath, Serpell investigated and monitored the performance of bacteria with and without calcium ion in cracked-concrete specimen aimed to examine the parameters that could promote the productivity of calcium carbonate [4]. Algaifi et al investigated factors affecting the rate of microbial calcium precipitation as well as bacterial growth inside the concrete through four main sub sequential areas – firstly, a new native strain was isolated, identified and screened, secondly the bacterial growth at crack mouth zones. Thirdly, the influential factors that affected the urea degradation and calcium carbonate precipitation. Finally the impact of bacteria on concrete characteristics. The microbial calcium carbonate was formed due to the metabolic activity of the Ureolytic bacteria, in which urea was decomposed to carbonate ions via bacterial urease enzyme. Subsequently, the carbonate ion reacted with the calcium ion to induce crystal formation of calcium carbonate [4]. Durga et al implemented bio concrete for self- healing. The computation and characterization of self-healing products was done by ultrasonic pulse velocities values. There is an increase in velocities with increase in time period showing the nature of impermeable concrete indicating the decrease in crack width by calcium carbonate formation [8]. Durga et al finds that there is an improvement in compressive strength for bacterial mix samples of 64.25 MPa compared to control samples. There is an increase of 11% flexural strength after cracking for 28 days curing of bacterial mix specimens by the excretion of urease enzyme of biomaterial [8].

2.2.2. Using bacterial carrier

Ronaldas et al employs biological activity in self-healing technology. In this approach the microorganisms and nutrients are placed directly into the concrete or protected by capsules. The use of calcium carbonate-producing bacteria to heal the cracks was defined as one of the most efficient and sustainable self-healing approaches since the generated healing agent CaCO3 is fully compatible with the concrete matrix. Figure (5) explains crack healing as a result of calcium carbonate precipitation [17]. Spore-forming bacteria are selected to ensure the resistance of the microorganisms to the harsh environment of the cement matrix, the ability to withstand mechanical stress, and high survivability rate in concrete [6]. Various approaches were used to minimise the mortality of bacteria. The typical techniques are the following: immersion of spores into lightweight porous aggregates, the incorporation of the biological product to silica gel, polyurethane, or graphite nanoparticles. Lightweight aggregates (such as expanded clay or perlite) are the promising raw materials for production of the bacterial carrier because of a relatively low price, compatibility to the concrete matrix, and simplicity of the bacteria spores immersion to the protection carriers [6].

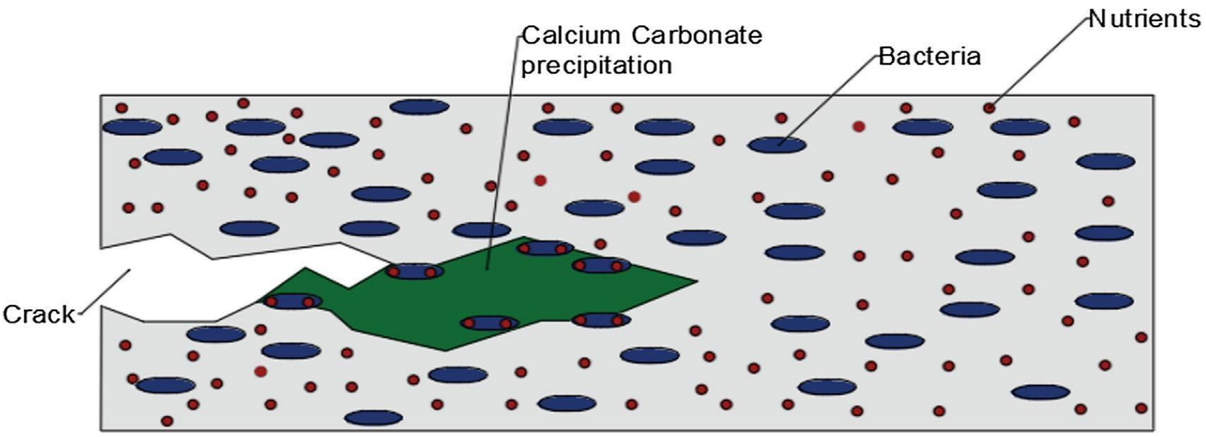

Figure 5 - Crack healing as result of calcium carbonate precipitation from bacteria

2.3. Micro encapsulation and method of encapsulation

Encapsulation healing techniques are function of capsule viscosity, shell thickness, diameter and surface. This technique is capable of extending active duration and releasing pattern of chemical/biological healing agents in concrete. A lot of researches suggested that this process is versatile and effective because of its efficiency to regain concrete's properties like mechanical and durability. Additionally, encapsulation techniques are facing repeatability challenge as concrete structures damages for multiple times and capsules deliver limited amount of healing agents in the crack of concrete due to which long time usability is not possible [10]. Different encapsulation materials for instance polymers, light-weight aggregates, glass and ceramic tubes, etc. are being used for development of self-healing phenomenon in cement matrix. Among mentioned encapsulating materials, polymeric capsules are being used widely by preparing them through an oil-in-water dispersion phenomenon of polymeric material. In order to make strong Urea (NH2CON2) and formaldehyde (CH2O) capsule shell, NH2CON2and CH2O are generally reacted in liquid phase. The pre polymer formed by mentioned reaction in liquid phase can be taken out to give somewhat rough texture to capsules [10]. Du et al investigated the effect of temperatures on self-healing capability of concrete with different shell composition microcapsule containing toluene di isocyanate. This is investigated under the temperature of 10 degree Celsius, 30, 50 and 60 degree Celsius. Du et al found the microcapsule is composed of two parts: the shell and the core. At present, most microcapsules use thermosetting materials as the shell, such as: melamine formaldehyde, polyuria formaldehyde and urea formaldehyde. However, the shell prepared by thermosetting materials have relatively high strength, it is hard to be ruptured by crack tip stress and release healing agent. To solve this problem, some scientists use thermoplastic materials such as paraffin, polyethylene or polypropylene as shell to prepare micro capsules. The paraffin was used as shell material to prepare microcapsules in previous published article. Although these microcapsules were easier to rupture under external force, the mechanical property of shell was low, which increased the risk of microcapsules rupture during concrete mixing process. Moreover, the melting point of paraffin is relatively low (around 60 degree C). If the microcapsules are used in high temperature areas such as tropical deserts or desert climates, when the ambient temperature rises, the paraffin will become soft and the healing agent cannot flow out in time to repair the cracks [11]. Huseien et al describes the mechanism of self-healing in cementitious material, hollow fibres store some functional materials' components (act as healing agent) inside of the empty spaces that form a composite network matrix. Healing agent flows out of these hollow spaces to repair the crack instantly. The implementation of microencapsulation with self-healing products release the healing agent into the crack surface via capillary action. There after the healing agent comes in contact with the embedded catalyst inducing polymerization and thus closing of the surrounding cracks [13]. Dry used methyl-methacrylate as the healing agent in a hollow porous polypropylene fibre capsule; this method provided an increased flexural strength of the mix. Joseph et al. and Li et al. utilized cyanoacrylate for single hollowed capsule and an increase in stiffness was obtained. Van Tittelboom et al. and Karaiskos et al. utilized polyurethane-tabulated hollowed capsules. Van Tittelboom placed long capsules in contact with steel reinforcement and short capsules embedded in the concrete while Karaiskos embedded capsules in a grid and attached to the reinforcement bars. Other researchers used various healing agents via the encapsulation method for crack healing [17]. Various stages incorporate encapsulated bacterial precipitation in concrete is described through figure (6) [10].

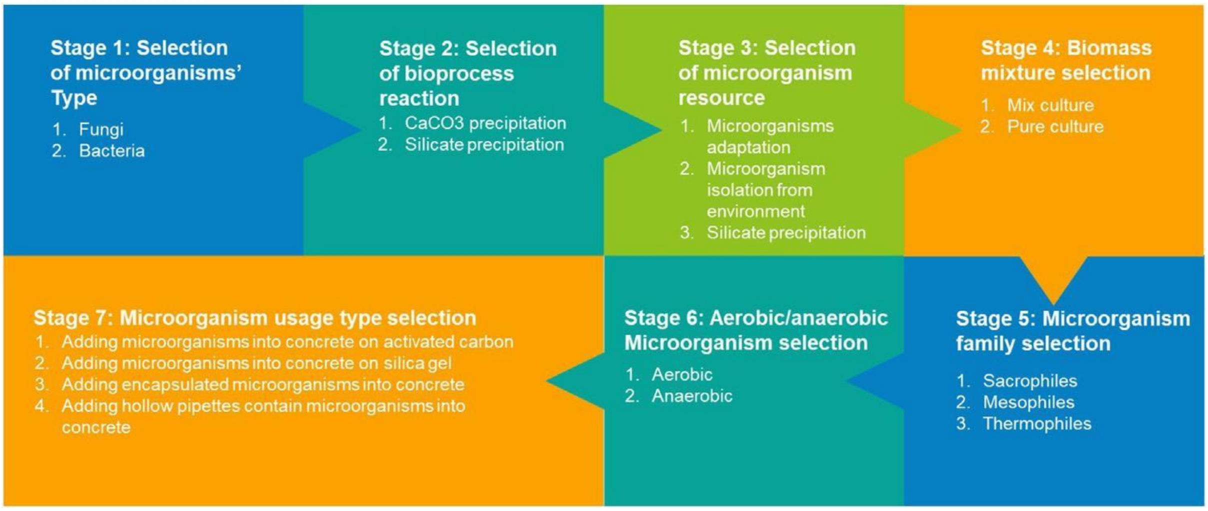

Figure 6 - Various stages incorporate encapsulated bacterial precipitation in concrete.

Vascular approach for concrete self-healing is another method for delivering healing agents into the concrete specimen; this method mimics the vascular structure of the human body. It consists of individual or a network set of hollowed tubes placed inside the concrete and the healing agent is supplied externally (Figure 7), therefore the system is practical for single or multiple healing Agents [17].

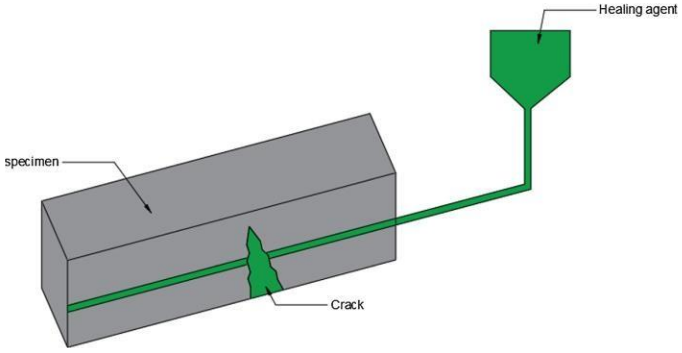

Figure 7- Vascular system approach for crack healing.

2.4. Using Chemical Agent

GAO et al introduces a new kind of hydrogel cross linked by alginate, chitosan and calcium ions was introduced. It was observed that the addition of chitosan improved the swelling properties of calcium alginate [7]. The interaction between amino groups of chitosan and carboxylic acid groups of alginates is mainly electrostatic force in a lower pH while it is mainly hydrogen bond at a higher pH. When the content of chitosan is 1.0% or 1.5%, the interaction of the NH3þ between chitosan molecules was weakened due to the increase of pH, which caused the decrease of swelling ratio. As for the hydrogel containing no chitosan or 0.5% chitosan, the swelling ratio at pH 9 is lower than at pH 6 and pH 12. It may because a part of -COOH got a second reaction with Ca2þ contained in hydrogel, which didn't react with -COO- before. The cross-linking reaction between -COO- and Ca2þ is very fast, which may cause some -COO- cannot react with Ca2þ for the existing of β-D-mannuronic acid (M) on alginate. When at pH 9, a moderate swelling of hydrogel prompted the movement of Ca2þ and then the reaction between -COO- and Ca2þ decrease the swelling ratio of hydrogel [7].

2.5. Using Polymer

Guo et al implemented UV adhesive as healing agent. The shell of capsule possesses three functional layers and each layer plays a different role. The inner layer of the capsule's shell is water soluble cellulose or gelatine, which acts as a temporary container for the healing agent. The middle layer of the shell is a cementitious waterproofing mortar layer. There are two functions of this layer, i) protecting the UV-curing adhesive from environmental light and ii) increasing the surface roughness of capsules and enhancing the bond strength between capsules and concrete matrix. Since the waterproofing mortar was found not to fully insulate water as the capsule collapsed once then it was immersed in water for few minutes followed by releasing the healing agent out, the outermost layer of the shell was coated with an acrylic acid-based polymer coating to further improve the waterproofing effect of the cementitious capsules. This polymer coating has a strong absorption capacity and could permeate into the pores and micro-cracks of the cementitious layer, protecting the inner shell and healing agent from being affected by the outside harsh environment [14]. Reddy et al focussed on artificial approaches like the addition of crystalline admixtures, polymers, and fibers to improve the strength of concrete by healing the cracks. Crystalline admixtures are the materials used in self-healing concrete. Many investigations concluded there is an increase in the mechanical properties and a decrease in water permeability of concrete by the addition of these admixtures, since it has hydrophilic properties. When this admixture is added to concrete it increases the stiffness and prevents the corrosion of steel due to alkaline attacks. When the concrete is exposed to water, the crystalline admixture forms into the needle-like structure and closes the cracks, which thereby reduce the permeability and also acts as a waterproofing agent. Therefore, it will be more useful in hydraulic structures like dams, water tanks, etc., to make concrete a water barrier [15]. Feng et al prepared a capsule consist of core material as cement or combination of cement and sap (super absorbent polymer), epoxy resin coating and a layer of sand. Cracks with initial crack width of 100-200 micro meter were highly healed and some cracks were completely closed. They prepared two types of capsules SC and WSC. SC consist cement + PEG and WSC consists of cement + SAP + PEG. SAP plays a role in squeezing cement out, accelerating diffusion of water into capsules. It promotes the contact between water and cement in capsules, which could be the reason why the hydration heat release rate and the total heat release of SC capsules were higher than that of WSC capsules, and length of acceleration period of SC capsules was shortened [2].

2.6. Using Fibre

Nasim et al presented a study of four mixes are cast, control mix (M1), 0.1% of PVA fibre by volume mix (M2), 20% partial replacement of cement with fly ash mix (M3) and 2% of CA by mass of cement mix (M4). The cracks were formed by applying the compressive load for early-age cracks after 3 days of curing. The materials in this study were cement, fly ash, superplasticizer, water, coarse aggregate materials, fine aggregate materials, CA and PVA fibers. The OPC-43 grade type of cement has been used. The sizes of 12–10 mm are selected as coarse aggregate and river sand is a fine aggregate. In this research four mixes are cast, control mix (M1), 0.1% of PVA fibre by volume mix (M2), partial replacement of cement with fly ash mix (M3) by 20 percent and 2% of crystalline admixture (CA) by mass of cement mix (M4) [9]. Su et al presented mechanism of the coupled effect of fibre and bacteria on self-healing efficiency of concrete. The results confirmed that the coupled effect of bacteria and fibre could result in higher repair efficiency, better mechanical properties and water resistance recovery. In addition, the significance of EPS in inducing the deposition of calcium carbonates on fibers was determined by analysing the induction effects of microbial cells and EPS respectively. Finally, biological staining was used to observe the role of biological organic matter in the repairing process [18]. Self-healing studies of engineered cementitious composite (ECC) showed that the fibers can enhance the self-healing of the matrix by accelerating calcium carbonate precipitation. In addition, due to the hydrophilic and hydrophobic properties, PVA fibre has better crack bridging ability than PP fibre and improves the self-healing efficiency [20,21], the calcium carbonate attached to the fibre gradually filled the cracks. At the same time, under the action of microbial mineralization, the adverse effect of the hydrophobicity of synthetic fibers on calcium carbonate deposition can be avoided [18]. The combination of non-hydrophilic PP fibers and microorganisms was used in concrete to observe the acceleration effect on self-healing. A variety of evaluation methods were used to evaluate the healing efficiency; in particular, the distribution of repair products in the cracks was recorded in the early stage of the repair process. In addition, microbial cells and microbial extracellular polymeric substances (EPS) were separated, and then the two combinations of Cells + PP fibers and EPS + PP fibers were applied to deposit calcium carbonate in the solution to explore the mechanism of the composite effect of fibers and microorganisms [18].

3. Limitations

According to the study of Jonkers et al when bacteria and their nutrients are directly added to concrete during mixing, the bacteria can survive for maximum of four months in the concrete, which is detrimental of long term and sustainable repair of concrete crack. Wang et al used micro capsule for self-healing of concrete crack which was effective but compressive strength is declined by 15%-34% when the dosage of 1% to 4% of microcapsule were added [1]. The compressive strength reduction was validated by Lee et al. and Hasholt et al., who concluded that the initial swelling of SAP generates a reasonable amount of SAP voids which can be classified as macro pores (>50 nm in diameter). SAP voids were generated through the initial swelling of SAP [3]. Snoeck et al. further explained that in fresh mix, macro pores spontaneously form and become occupied by swollen SAP particles. Later, the concrete pore solution is consumed by cement hydration, which reduces the ambient moisture at locations of SAP deposition. Subsequently SAP releases the entrapped water, causing the SAP to shrink. After SAP voids form, they result in increases in the total porosity of the concrete system. In contrast, some studies reported that concrete in presence of SAP possibly shows decrease or increase in strength depending on which side of the mechanism is dominant. Strength loss predominantly results from porosity increases. Strength gain is characterized by a combination of the three mechanisms. First, strength increases with decrease in w/c ratio. Second, strength improvement is a function of the densification of the pore structure and the enhanced hydration degree predominated by an effective internal curing of SAP. Third, SAP mitigates the development of micro cracks from self-desiccation. In cases of SAP content higher than 4%, it was found that the effect of the porous matrix is dominant, which results in compressive strength reductions at higher SAP contents [3].

4. Possibility Of Post Fire Self-Healing

It is evident that the addition of steel fibers can restrain the propagation of micro-cracks in concrete under high temperature. Besides, incorporating PP fibers are effective in providing channels for the release of internal pressure via melting at high temperatures and connecting internal pores [43]. When tunnel fire occurs, a sharp increase in vapor pressure inside tunnel concrete structures caused by high temperature gradients will give rise to the explosive spalling of Self-compacting concrete (SCC), thus leading to the collapse of tunnel structure [44, 45]. The organic polymer (i.e., usually epoxy) in the FRP composites has poor resistance to elevated temperatures under which both its strength and stiffness are degraded [46, 47]. During a fire, the FRP composites may also generate toxic gases. Therefore, recent attempts have been made to replace the epoxy in the FRP composites using inorganic/cementitious materials to develop fiber reinforced inorganic polymer (FRiP) composites [often termed as ‘‘fiber reinforced cementitious matrix (FRCM)” as well] to gain improved fire resistance, and in the meantime, to achieve more compatibility between the strengthening material and the concrete substrate [48-52]. 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.

Table describes bacteria type for self-healing with their advantages and disadvantages in form of result.

Methods	Mechanism	Result	references
A bio capsule by coating bacterial spores with the prepared cementitious (carbide slag, fly ash, and desulfurized gypsum) material.	Bacterial spore powder was added to a suitable quantity of water for homogeneous dispersion. The mixture of core-material substances	• Addition of bio capsules at a dosage of 5% of the cement mass led to full healing of 150–550 µm width cracks.	[1]

	(excluding the bacterial spore powder) was then added to the homogeneously dispersed bacterial spore powder, and they were well mixed to obtain a lumpy mixture that was further kneaded until it was no longer sticky. The lumpy mixture was then slowly added into a multi-purpose pelletizer 50 g at a time, to perform pressing, extruding and pelleting, followed by rolling, drying and sieving	• The bio capsule saw a substantial mass loss. • After healing, the permeability of specimens containing the bio capsule declined by about two orders of magnitude as compared with reference specimens.	
combination of cement and superabsorbent polymers (SAPs), Which were granulated by poly (ethylene glycol) followed by a waterproof layer	Core materials in capsules were react with water with dissolution of PEG (poly ethylene glycol) and swelling of SAP swelled in cracks.	• Specimens incorporated ratio for cracks below 400 µm and even inside capsules showed high sealing cracks wider than 200	[2]

(i.e., epoxy resin and sand).		µm could be bridged due to capsules with SAP. • Recovery of water tightness, flexural and compressive strength were obtained.	
Eight mix proportions with varying fly ash and SAP replacement ratios were examined	crack closure to be dependent on several mechanisms, such as those incorporating autogenous self-healing by the continued hydration of unreacted cement, calcium carbonate crystallization, the deposition of impurities in water, and the swelling and expansion of C-S-H gel including C-S-H formation from pozzolanic reactions	• Compressive strength reduction. • The addition of fly ash improves damage prevention. Specimens containing fly ash obtain finer cracks under cracking loads than specimens without fly ash.	[3] , [19] , [20]

Natural fibers namely, coir, flax, and jute fibers to carry bacterial spores for self-healing in concrete.	The natural fibers act as good carriers of bacteria by keeping them dormant but alive, and ready to activate on exposure to extra oxygen and moisture/water availability Upon cracks formation and growth in concrete. In all the fibre reinforced microbial formulations, as soon as the crack was formed, fibers loaded with bacterial spores became exposed to air and moisture and the crack was repaired due to biosynthesized CaCO3 product deposited in the cracked region.	• bacteria Addition improved the compressive strength of concrete.	[5]
hydrogel cross linked by alginate,		• A healing crack of 4 cm	[7]

chitosan and calcium ions	Bacteria are able to form calcium carbonate (CaCO3) precipitations.	length and 1 mm width was observed when using cement PO325, with the addition of bacterial spores encapsulated by hydrogel containing no chitosan. • Increasing of strength.	
four mixes are cast, control mix (M1), 0.1% of PVA fibre by volume mix (M2), 20% partial replacement of Cement with fly ash mix (M3) and 2% of CA (crystalline admixture) by mass of cement mix (M4).	CA was added to produce extra C-S-H gel and Pore locking deposits by reacting with the calcium hydroxide. This improves the microstructure of the cementitious lattice clearly, on the basis that the denser lattice formation results and the voids are reduced and the pores interconnect.	• Recovery of compressive strengthand electrical resistivity of the cracked CA concrete samples has the highest self-healing capability. • The compressive strength of cracked CA concrete (M4) shows an	[9] , [21] , [22]

	In general, as concrete aged, due to further hydration of the cement and progressive hardening Of the concrete resistivity has increased.	increase of 36.6 percent as compared to cracked control concrete (M1).	
Polyurethane/urea formaldehyde used as shell material. Encapsulated in Sodium silicate with 2.5 – 5% replacement of cement by weight.	Mechanism not mentioned	• Reduces crack width and transmission of ultrasonic wave.	[10] , [23]
Poly (urea formaldehyde) used as shell material and encapsulated in epoxy with 1-4 % replacement of cement by weight.	Mechanism not mentioned	• Increases flexural strength	[10] , [24]
Urea formaldehyde as shell material and encapsulated in epoxy with 0-9% replacement of cement by weight.	Mechanism not mentioned	• Reduces damage index • Reduces porosity, chloride diffusion and Permeability.	[10] , [25-30]

		• Increases compressive, tensile strength and dynamic elastic modulus.	
Urea formaldehyde as shell material and encapsulated in Ca (NO3)2 with 0.25 -2% replacement of cement by weight.	Mechanism not mentioned	• Increases elastic modulus and surface resistivity	[10] , [31-33]
Urea formaldehyde as shell material and encapsulated in sodium silicate with 0.5-5% replacement of cement by weight.	Mechanism not mentioned	• Increases stiffness	[10] ,[34]
Urea formaldehyde as shell material and encapsulated in Dicyclopentadiene with 0.25 % replacement of cement by weight.	Mechanism not mentioned	• Increases stiffness	[10] , [34]
Poly urea as shell material and encapsulated in sodium silicate with 0.8 % replacement of cement by weight.	Mechanism not mentioned	• Reduces capillary absorption	[10] , [35]

Poly styrene-divinylbenzene as shell material encapsulated in epoxy with 0-2 % replacement of cement by weight.	Mechanism not mentioned	• Increases fracture energy	[10] , [36]
Melamine as shell material and encapsulated in epoxy with 1-4% replacement of cement by weight.	Mechanism not mentioned	• Reduces water absorption • Increases flexural strength	[10] , [37]
Spore forming bacteria (species not Mentioned) and directly added.	Mechanism not mentioned	• High early healing was observed by water curing. • Higher the cracking age, lower is the extent of healing.	[38]
Bacillus directly added	Decomposition of calcium source to precipitate carbonate	• Calcium source affects healing ratio-calcium glutamate performs better than lactate • Bacteria remained	[39]

		viable for 4 months	
Bacillus cohnii encapsulated in clay aggregate	Metabolic conversion of calcium lactate	• Crack width of 0.15 mm with length 8 cm completely sealed. • No loss of viability up to 6 months.	[40]
Bacillus Sphaericus immobilized in PU and silica gel inside glass	Ureolytic decomposition of calcium nitrate	• PU immobilized bacteria specimens showed lowest permeability • Higher bacteria activity in silica sol • Higher strength recovery in case of PU immobilization	[41]
Bacillus Sphaericus encapsulated in Diatomaceous earth	Ureolytic decomposition of calcium nitrate	• Highest reduction of water absorption was observed in bacteria	[42]

		containing specimen. • Dosage of DE must be carefully adjusted because it causes loss in concrete workability.	

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