DOI https: //doi. org/10.1007/s11595-019-2171-2

Self-Healing Concrete with Crystalline Admixture—A Review

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Abstract: The scope of the present paper is to understand the effects of crystalline admixture on the self-healing capacity of the cementitious composites. Previous studies were examined and a conclusion was drawn to the effect that different additives to crystalline admixture tend to improve self-healing of concrete for larger cracks. It is recommended that initial treatment with chemical admixture can stimulate and heal further cracks and it has the better repeatability trend in mixing with the concretes and mechanical recovery is possible even under repetitive preloading. Effective self- healing with chemical admixtures even under open-air exposure, leads to study the importance of a service ability design parameter including the maximum allowable crack width by repeatability analysis as a function of the exposure with the concept of sealable crack width.

Key words: crystalline admixture; permeability reducer admixture; cracking

1 Introduction

Concrete is used as construction material due to its fire resistance, high compressive strength and low expense. However concrete has small tensile strength[1] and hence is prone to cracking .Cracks reduce anti-chloride-corrosion, anti-permeability and anti-carbonisation in a great way[2]. This, in turn, reduces the durability and carrying capacity of structures and non-repair can lead to destruction and even collapse[3].

Self-healing materials can autonomously heal cracks, improve service life with reasonable cost, and thereby improve the sustainability of the structure[1,3] and guarantee for reinforcement in their entire life[4,5]. Concrete by itself has self-healing properties known as autogenous healing. In the past attempts have been made to induce autogenous healing process in cement such as the addition of Portland cement[6-9], applications of microencapsulated healing agents[10-13], the use of crystalline admixtures and bacterial concrete[14].

ACI Committee has reported that there is a better adoption of self-healing properties in self-healing concrete when there is an addition of crystalline admixture (CA) also known as permeability reducer admixtures[15]. Crystalline admixture materials react quickly with water and are used as hydrophilic materials. Calcium silicate hydrate (CSH) density is further enhanced which resists water penetration. In the presence of water, matrix components react with tricalcium silicate (C_3S). Crystalline deposits can withstand pressure up to 14 bars just like hydrophobic materials. However, the results are a mixed bag. For instance, crystalline admixture had a higher rate of self-healing in small cracks (less than 0.05 mm) while they were inefficient in more extensive cracks[16]. Combination of crystalline admixture and self-healing concrete achieved 400 μm[17] against 150 μm when there was no mixture. Admixtures have been analysed in different exposures[18,19] and methodologies based on mechanical strength, duration and recovery property that depend on the structure. Why cracks are formed are due to the expansion and shrinkage in concrete with temperature difference, applied force, structural mechanism, and dryness on the concrete surface. Fig.1 describes the different types of concrete cracks and their solutions are found in Table1. Fig.2 describes the self-healing process. The aim of this paper is to explore the crystalline admixture impacts on the self-healing capacity of concrete by either partially or entirely resealing the cracks and as in some cases to show recovery of mechanical properties. The study takes into account both high-performance and standard strength concrete fibre-reinforced cementitious concrete. The methods of the review are presented in Section 2. Section 3 critically reviews and interprets different studies used in the analysis. Sections 4 and 5 discuss and conclude the studies along with future recommendations.

(Received: May 26, 2018; Accepted: June 3, 2019)
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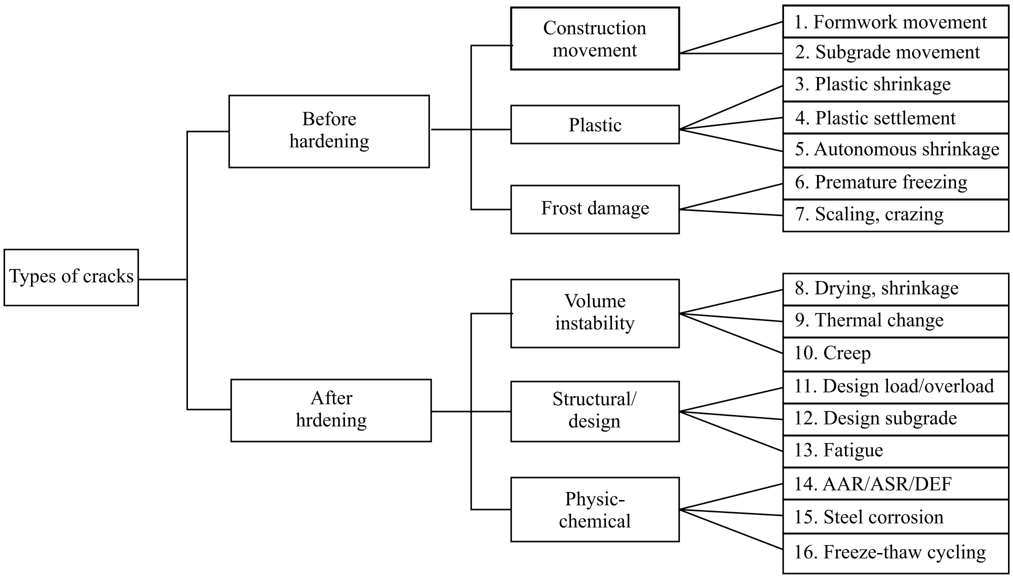

Fig.1 Classification of crack

Table 1 Causes and solutions of different types of cracks

No.	Crack type	Description	Causes and Solutions
1	Plastic-shrinkage cracking	Cracks that run to the mid-depth of the concrete are distributed across the surface unevenly and are usually short in length.	Mostly, it occurs while concrete is curing. The surface of the concrete dries too rapidly compared the pavement below.
2	Crazing/Map cracking/ Checking	A web of fine, shallow cracks across the surface of the concrete.	During the process of curing, the surface of concrete dries faster than the interior, but the surface drying occurs at a lesser depth.
3	Hairline cracking	Very thin but deep cracks	Due to the settlement of the concrete while it is curing. Due to their depth, these cracks can allow for more severe cracking once the concrete is hardened.
4	Pop-Outs	Conical depressions in the concrete surface	It occurs when a piece of aggregate near the concrete surface is particularly absorbent, causing it to expand and pop out of the surface of the concrete.
5	Scaling	Small pockmarks on the concrete surface, exposing aggregate underneath.	If concrete does have an adequate finish to prevent water penetration, water that seeps into the pavement will expand when it freezes, pushing off pieces of the concrete surface.
6	Spalling	Surface depressions that are larger and deeper than scaling, often linear when following the length of a rebar. Also, it is caused by pressure under the surface of the concrete.	Spalling that exposes corroded metal can be particularly problematic because the corrosion is likely to accelerate due to exposure to air and water.
7	D-Cracking	Cracks that runs roughly parallel or stems from a concrete joint and are thicker than surface cracks.	Due to moisture infiltration at the joint
8	Offset cracking	Cracks where the concrete on one side of the break is lower than the pavement on the other hand.	Due to uneven surfaces below the concrete, such as subgrade settlement or pressure from objects such as tree roots, previously-placed concrete, or rebar.

2 Methods

The present review employes various standard sources for the literature search which includes scholarly web search engine such as Google Scholar and IEEE transaction and journals including Elsevier, Springer, and ACM and so on. In addition, numbers of manual searches were conducted within the review papers and individual documents' reference sections. A total of 22 different research studies matched the search criteria for this review.

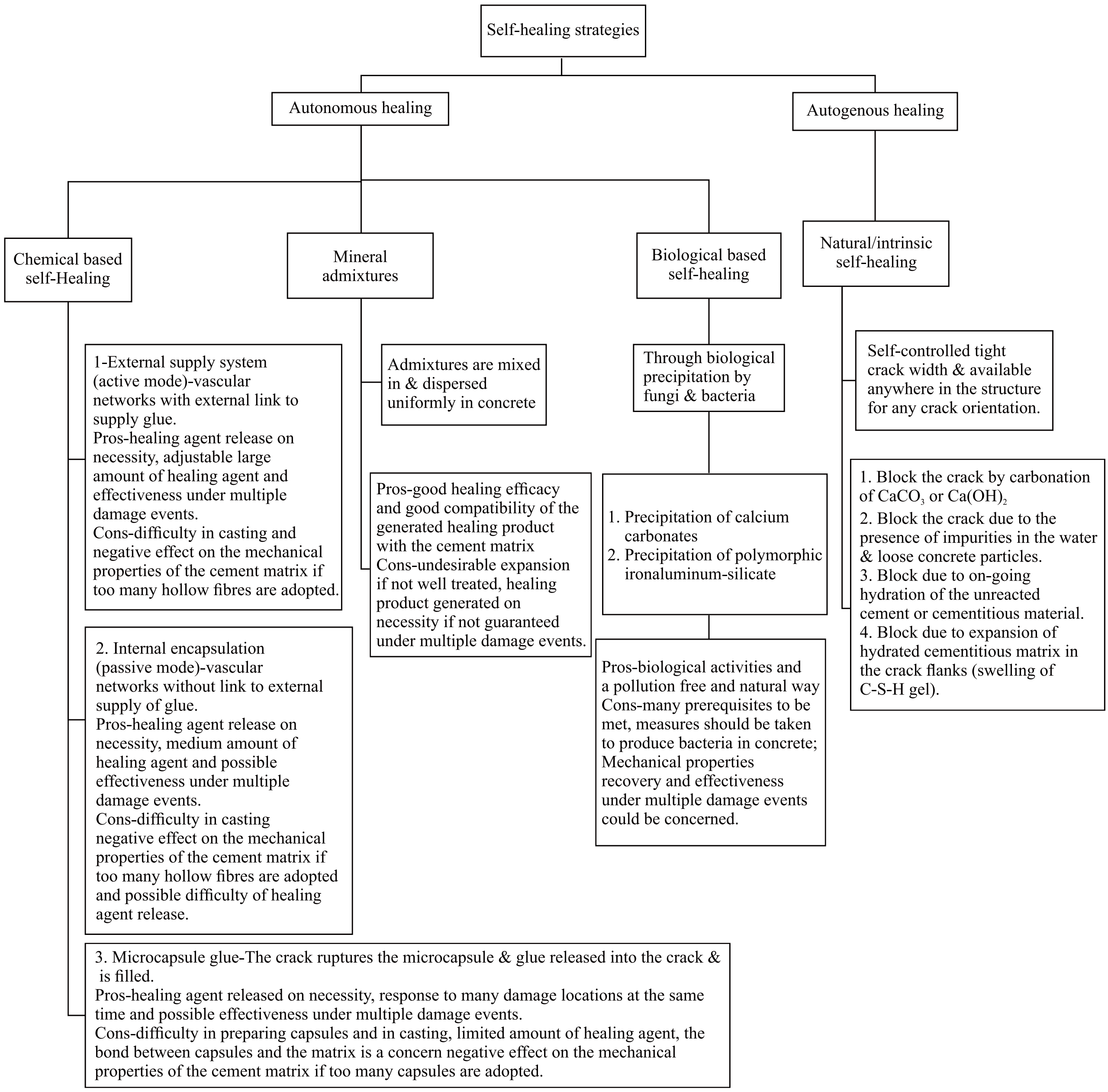

Fig. 2 Classification of self-healing process in concrete by Meharie *et al*[20]

3 Results

An extensive researches on SHC are listed in Table 2. Section 3.1 analyses the various healing materials, methods and results from the selected probes. The studies on self-healing concrete were based on admixture materials, crack type, different combinations of additives, different research approaches and different environmental exposures. In the initial stages , in order to offer better admixture to heal the concrete, different kinds of cracks and different admixtures were examined.

3.1 General description of the study

Examination on the basis of different environmental exposures to evaluate the best crystalline admixture is examined by Roig-Flores *et al*[16], Roig-Flores *et al*[21], Roig-Flores *et al*[23] and Reddy and Ravitheja[22]. Examining the influence of crystalline admixture constitution on the basis of mechanical and physical properties was done by Joa *et al*[26], Ferrara and Krelani[24] and Reddy *et al*[25]. The durability and waterproofing ability of concrete were examined by Pazderka and Hajkova[27]. Other different additives that were added to the crystalline admixture and its effect on the self- healing process were examined by Sisomphon *et al*[28,29] and Jaroenratanapirom and Sahamitmongkol[30]. Further, the effect of self-healing with and without crystalline

Table 2 Summary of existing work on self healing concrete

	Author name	Title	Aim/Objective	Recommendation	Limitations
1	Roig-Flores *et al*[21]	Self-Healing capability of concrete with crystalline admixtures of different environments	- Analyse the effect of crystalline admixture to enhance self-healing - Influence of environmental exposure in self-healing of concrete with and without crystalline admixture - Evaluation of self-healing properties based on global permeability and different geometrical characteristics	Samples with crystalline admixture had stable and reliable behaviour in healing behaviour, featuring lower dispersion and clearer trends.	Limits were shown of the self-healing capability of crystalline admixture for cracks wider than 150 μm, while the combination of both agents achieved complete self-healing for cracks up to 400 μm after 30 days of water immersion.
2	Roig-Flores *et al*[16]	Self-healing capability of concrete containing crystalline admixture in different exposure conditions	Quantify the self-healing effectiveness of crystalline admixtures as self-healing agents and to compare the results of concrete specimens with and without the admixture under different environmental exposures	The presence of two centimetres water layer on top of the specimen is enough to make the self-healing rate to increase up to 80%	It is important for the presence of water for the self-healing reactions suggesting a possible shrinkage compensation caused by crystalline admixtures
3	Reddy and Ravitheja[22]	Study on strength characteristics of self-healing concrete with crystalline admixture	Quantify the self-healing effectiveness of crystalline admixtures as a self-healing agent and compare the results of concrete specimens with and without the crystalline admixture under different environment exposure and influence of pre-cracking time on the self-healing behaviour.	Pre-cracking age does not affect the healing process. The specimen healed and regained mechanical properties the same as the control concrete at 2nd day and 28th day.	The self-healing process does not depend on age of crack development.
4	Roig-Flores *et al*[23]	Effect of crystalline admixtures on the self-healing capability of early-age concrete studied by means of permeability and crack closing tests	Self-healing properties of early-age concrete, engineered using a crystalline admixture of 4% by the weight of cement, by measuring the permeability of cracked specimens and their crack width, compare the self-healing behaviour of concrete with and without crystalline admixtures under three different exposure conditions.	Crack closing ratio featured similar trends compared with the healing ratio, but it may overestimate the phenomenon when the elements are exposed to wet/ dry cycles. Thus it is recommended that the closing ratio is always assisted by a second parameter or technique for a proper evaluation of self-healing	Healing exposure for cracks up to 0.40 mm, the values are around 0.50 mm, which suggests cycling regimes under water immersion followed by drying periods will not be healed effectively within 42 days.
5	Ferrara and Krelani[24]	Engineering self-healing capacity of cement-based materials through crystalline admixtures	Characterization will be performed of the effects of crystalline admixtures, employed as porosity reducing admixtures, on the self-healing capacity of the cementitious composites, *i e*, their capacity to completely or partially re-seal cracks and, in case, also exhibit recovery of mechanical properties.	Some internal chemical pre-stressing of fibres may be triggered by the expansive reactions of the admixture.	High performance fibre reinforced cementitious composite has some internal chemical pre-stressing of fibres which may be triggered by the expansive reactions of the admixtures.
6	Reddy *et al*[25]	Study of the effect of silica fume on the self-healing ability of high strength concrete with crystalline admixture	Analysing the self-healing capability of high strength concrete (M70) with silica fume and crystalline admixture in four types of environmental exposures	Split tensile strength of HSC (M70) with partial replacement of cement by silica fume is increased up to 10% replacement of sand and with further increase in silica fumes the split tensile strength decreases.	Mechanical properties of pre-cracked specimens with 10% of silica fume and 1.1% of crystalline admixture have complete crack closing ability and 100% strength regained for water immersion, wet/ dry and partially regained for water contact and air exposure.

	Author name	Title	Aim/Objective	Recommendation	Limitations
7	Joa *et al*[26]	Effect of incorporation of self-healing admixture on physical and mechanical properties of mortars	Studying the effect of crystalline admixture a type of self-healing admixture on mechanical and physical properties of mortars	Crystalline admixture application in smaller amounts than the amount of 2 % of the cement weight can be recommended which determines the minimum amount of an admixture to ensure a waterproof ability of concrete.	There is a capability of self-healing Admixtures to produce more hydrated products and healing the pores during the hydration by making it suitable for improving mechanical and physical performances.
8	Pazderka and Hajkova[27]	Crystalline admixture and their effect on selected properties of concrete	Compressive strength comparison between concrete with an admixture and the reference concrete. Carry out the water pressure test in different time intervals during the initial phase of the cement hydration.	The crystalline admixture application in smaller amounts than the amount of 2 % of the cement weight can be recommended depending on the minimum amount of an admixture to ensure a waterproof ability of concrete.	Concrete structure with crystalline admixture has a guaranteed waterproofing ability after the standard hardening time of concrete (28 days), though concrete with admixture showed waterproofing effect after 12 days, stating a risk of a slower onset of the waterproofing.
9	Sisomphon *et al*[28]	Self-healing of surface cracks in mortars with expansive additive and crystalline additive	The self-healing potential of cement-based materials incorporating calcium sulfoaluminate based expansive additive (CSA) and crystalline additive (CA)	Calcium carbonate was found to be the major healing product. A significant amount of calcium carbonate precipitation can be observed, particular on the mouth of crack.	Mechanism is not highly promising in healing typical cracks in concrete because of the limited remaining potential and difficulties in optimising the performance.
10	Sisomphon and Copuroglu[29]	Self-healing mortars by using different cementitious materials	The self-healing ability of mortars incorporating different cementitious materials.	The net-like formation of ettringite is beneficial to the formation of calcium carbonate particularly at the near surface area.	Mechanism is not highly promising in healing typical cracks in concrete because of the limited remaining potential and difficulties in optimising the performance.
11	Jaroenratanapirom and Sahamitmongkol[30]	Effects of different mineral additives and cracking ages on self-healing performance of mortar	To investigate self-healing capability of mortar with different mineral additives by using surface crack width as the indicator of damage degree	For a wider crack, crystalline admixture became less effective while the mortar with silica fume (10% added) became more effective in self-healing, especially when crack was generated at later age (28 days).	The products healing the cracks found in all mortars were crystal-like materials. However, the crystal forms are different in each type of binder. There are two possibilities that are different crack-filling substance or same substances but different forming process.
12	Ferrara *et al*[31]	On the use of crystalline admixtures in cement based construction materials: from porosity reducers to promoters of self-healing	Aims at a thorough characterization of the effects of crystalline admixtures, currently employed as porosity reducing admixtures, on the self-healing capacity of the cementitious composites	Long-term performance and repeatability of the healing capacity, including effects of sustained throughcrack stresses should be addressed	The problem has been investigated with reference to both a normal strength concrete (NSC) and a high performance fibre reinforced cementitious composite (HPFRCC)

	Author name	Title	Aim/Objective	Recommendation	Limitations
13	Ferrara *et al*[32]	A “fracture testing” based approach to assess crack healing of concrete with and without crystalline admixtures	Characterization of both autogenic and engineered self-healing of ordinary concrete, with or without a crystalline admixture.	Influence of through-crack stress state, repetition of cracking and healing cycles, and a thorough investigation of fibre reinforced concrete and cementitious composites, and the identification of post-cracking residual strength of the material and its degradation/evolution over time	The function of the exposure conditions plays a crucial role in the development of a durability based design approach.
14	Escoffres *et al*[33]	Effect of a crystalline admixture on the self-healing capability of high-performance fiber reinforced concretes in service conditions	To measure the water permeability and self-healing of a high performance concrete (HPC), a HPC with fibers (HPFRC) and a HPC with fibers and crystalline admixture (HPFRC-CA) were investigated.	Mg-based crystalline admixture has favored aragonite formation in cracks of the high-performance fiber reinforced concrete, which has slowed down the self-healing process measured by water permeability, but provided a greater mechanical recovery under tension to the material.	An explanation of this observation could be related to the growth rate of aragonite and calcite. Information in literature about growth rate of various forms of calcium carbonate is limited.
15	Pazderka[34]	Concrete with Crystalline Admixture for Ventilated Tunnel Against Moisture	To examine the crystalline admixtures and their effect on selected properties of concrete	A suitable solution is ventilated tunnel based on the special shaped concrete blocks whose durability is ensured by using of concrete with crystalline admixture. The simplicity of assembly results in a lower cost and faster construction.	Presently the ventilated tunnels are designed as masonry structure whose durability in contact with the ground moisture is limited.
16	Albertini[35]	Self-Healing Capacity of Fiber Reinforced Concretes with Different Additions	To investigate the capacity of different additions of fiber reinforced concrete with medium to high water to cement ratios, subjecting to wide cracks.	Investigation on the effect of longer time of conditioning on steel fibers	Investigation on the effect of the application of tensile stress during conditioning is limited.
17	Al-Kheetan *et al*[36]	Development of hydrophobic concrete by adding dual-crystalline admixture at mixing stage	To investigate the performance of a crystallizing material mixed at mixing stage and in different percentages.	Regardless of increasing the workability of concrete when adding a high percentage (8%) of hydrophobic admixture, neither segregation nor thermal cracking has taken place	Despite the high slump in the fresh mixture, no segregation was observed in the matured concrete. There was a marginal reduction of strength when a high percentage of admixtures was used.
18	Cuenca and Ferrara[37]	Effects of Crystalline Admixtures on the Repeatability of Self Healing in Fiber Reinforced Concrete	To analyze the repeatability of autogenous and engineered self-healing in fiber reinforced concrete (FRC) with and without crystalline admixtures	The observed porosity suggests that, in addition to the aggressiveness of the solutions, the continuous flow of sewage plays a major role in accelerating the attack.	The evolution of the crack opening and of the mechanical behaviour after one or two cracking/healing cycles for different durations of the first healing period have been analyzed.

	Author name	Title	Aim/Objective	Recommendation	Limitations
19	Cuenca *et al*[38]	A methodology to assess crack-sealing effectiveness of crystalline admixtures under repeated cracking-healing cycles	To examine the effectiveness of crystalline admixtures on self- healing and autogenous character of steel fiber concretes by continuous cracking and healing experiments.	Initial treatment with chemical admixtures could stimulate and heal the future cracks. Healing products formed by the slow hydration and carbonation reactions between the cement and crystalline admixture. This study recommends the evidence of some ettringite crystals formed inside and heal the same cracks.	The self- healing capacity of fiber oriented materials is none. There is no evidence of healing capacity even though the fibers are preferentially oriented perpendicular to the crack.
20	Reddy *et al*[39]	Self-Healing Ability of High-Strength Fibre-Reinforced Concrete with Fly Ash and Crystalline Admixture	Analysing the self-healing capability of high strength concrete (M70) with fly ash and crystalline admixture in four types of environmental exposures.	Strength regain of HSC with partial replacement of cement by flyash is increased up to 20% replacement and with further increase in self healing efficiency.	Mechanical properties of pre-cracked specimens with 10% of flyash and 1.1% of crystalline admixture have complete crack closing ability and 100% strength regained for water immersion, wet/ dry and partially regained for water contact and also not in air exposure.
21	Borg *et al*[40]	Crack sealing capacity in chloride-rich environments of mortars containing different cement substitutes and crystalline admixtures	To evaluate the crack healing capacity of chloride constitutions in various concrete mixtures, adding supplementary cementitious materials and crystalline admixtures.	The good performance of mixes with crystalline admixture even under open-air exposure, as well as of other mixes paves the way to revise the significance of a serviceability design parameter such as the maximum allowable crack width as a function of the exposure with the concept of a sealable crack width.	Being a preliminary investigation, crack sealing has been only visually monitored, and further work is ongoing to investigate the chemical reactions occurring under the selected conditions
22	Cuenca *et al*[41]	Repeatability of self-healing in fiber reinforced concretes with and without crystalline admixtures: preliminary results	To investigate the self- healing capacity of crystalline admixtures on the intrinsic and engineered fiber reinforced concrete (FRC). To perform double edge wedge splitting (DEWS) test to examine the tensile behaviour of two different mixes.	Referring to the observations made with the digital microscope it was confirmed that the larger the initial crack width, the lower the percentage of crack closure.	Independent of the initial crack width value and the healing cycle (first or second), specimens healed in the open air were characterized by the lowest crack closure percentages. The most unfavourable exposure condition for healing was the exposure to open air.

admixtures was examined by Ferrara *et al* [31,32].

3.2 Self-healing capability with crystalline admixture in different environmental conditions

The life service of the building constructs is improved by adding self-healing materials which autonomously repair cracks and small damages. Furthermore, these types of materials could perform as a life saver for the future issues in the structure or expensive reparations. As reported by the ACI Committee, crystalline admixtures which are a type of permeability reducer admixture are characterized as hydrophilic in nature, which increases solubility in water. When mixed with water they form water-insoluble pore /crack blocking deposits that increases the concentration of calcium silicate hydrate (CSH) and resists water penetration. Controlled creation of specific damages (*e g*, cracks) and the evolution of such damages under different environment form the basis of a study of self-healing materials.

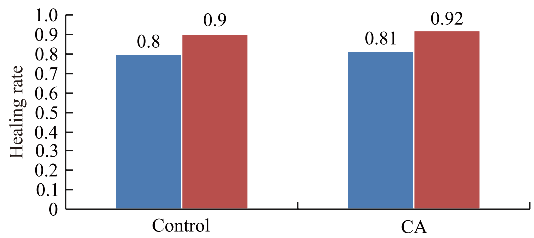

Fig.3 Average healing rate of WC

Table 3 Mix design of control and CA concrete

Material	Control	CA Concrete
Cement II/A-L 42.5 R/(kg/m^3)	350	350
Water/(kg/m^3)	157.5	157.5
Gravel (4-12 mm)/(kg/m^3)	950	959
Natural sand/(kg/m^3)	899	875
Fibers, Dramix 65/35/(kg/m^3)	40	40
Limestone powder (LP)/(kg/m^3)	50	36
Crystalline admixture (CA)/(kg/m^3)	–	14
Additional fine fraction: LP + CA/(kg/m^3)	50	50
Average slump/cm	13	15
Average compressive strength/MPa	53	61

From the results presented in Fig.3 which are based on the analysis of the study Roig-Flores *et al*[16] and Roig-Flores *et al*[23], it may be inferred that there are better results with CA than with control concrete. However, CA natural self-healing character alone could not support to bring complete self-healing. Hence the mix design of control and CA concrete is shown in Table 3.

The crack closing under various environmental conditions and under different exposures such as water immersion(WI), wet or dry cycles (WD),water contact(WC) and air exposure (AE) under laboratory conditions were examined by Reddy and Ravitheja[22] using the proportion of the crystalline admixture with 1.1 % weight of the cement.

The optic microscope was used to observe the physical closing of the crack and quantification was carried out through crack geometrical parameters. When water temperature is 30 °C, the healing is complete, and the healing behaviour is dependent on the exposure and the presence of 4% of crystalline admixture. When disclosures concrete is mixed with 1.1% crystalline admixture, it regains the split tensile strength and compressive strength as control concrete durability. When cement was replaced with silica fume[25] (5%, 10%, 15%) and with the addition of 1.1% crystalline admixture, all mixtures have a considerable amount of closing ability and strength regain capacity under different exposure conditions. Borg *et al*[40] assessed the crack sealing capacity in chloride environments of different concrete mixtures, incorporating supplementary cementitious materials as well as self-healing enhancing crystalline admixtures. The result showed that immersion under sea water showed better crack healing performance compared to distilled water, which indicates that the higher the chloride content, the better and faster the healing.

3.3 Effect of crystalline admixture on physical and mechanical properties

Including crystalline admixtures in construction material is a novel idea. However, a thorough investigation is needed before they can be included in building material.

Joa *et al*[26] examined the crystalline admixture of 3% by weight into cement and lime mortars. The modules of elasticity are found by dividing the stress and its corresponding strain . The mechanical properties of high performance fibre reinforced cementitious composites were examined by Ferrara and Krelani[24]. Ferrara *et al*[31,32] attempted to investigate and characterize the crystalline admixtures impacts on the self-healing capacity of the concrete material by assessing their capacity to partially or completely heal cracks and mechanical properties. The interaction between the crystalline admixture performance and the dispersed fibre reinforcement is favourable in 'chemical pre-stressing' of the same reinforcement, from which the materials' mechanical performance recovery has be largely in-

Table 4 Mix design of control and CA concrete

Material	Cement	*w/c* ratio	Coarse aggregate (20-12.5 mm)	Coarse aggregate (12.5-4.75 mm)	Sand	Steel fiber (0.51%)	Crystalline admixture (1.1%)	Compaction factor
Control concrete	425.5	0.45	599	599	656.5	40	-	0.87
C A concrete	420.82	0.45	599	599	656.5	40	4.68	0.87

creased up to levels even greater than the virgin uncracked materials' performance.

3.4 Waterproofing ability and durability of concrete with crystalline admixture

Crystalline materials include surface-applied spraying or coating, integral waterproofing admixtures and sealing and repairing mortars. Mainly, the waterproofing admixture is applied for the latest buildings with the foundation structure from waterproof concrete. Most of the literature in the field of concrete reinforcement has been focused mainly on the durability and waterproofing ability of the concrete by crystalline admixtures. Regardless of these two properties, other properties have not been credibly established so far. The other characteristics include the influence of the lifetime of waterproofing by the crystalline admixture in the cementitious materials. Furthermore, water vapour permeability is one of the critical challenges due to the surface condensation. Pazderka and Hajkova[27] conducted various experimental measurements for durability and waterproofing ability of concrete using crystalline admixture. The waterproofing effect of crystalline material is obtained by the reaction of various chemical components incorporated in the concrete material. The crystalline admixture has the potential to reduce the water vapour permeability of concrete by 16%-20%. Furthermore, water pressure test was also conducted for a range of time intervals. The initial phase of cement hydration showed complete waterproofing ability of concrete with a crystalline admixture only after 12 days. The mechanical properties such as compressive strength of the prepared concrete materials are also examined. The compressive strength of the specimens from concrete without admixture and concrete with 2% crystalline admixture were almost the same after 28 days.

The analysis of water permeability and self-healing of a high performance concrete (HPC) was conducted by Escoffres *et al*[33]. The potentials of HPC with fibers and crystalline admixture (HPFRC-CA) and HPC with fibers (HPFRC) were examined. The maximal crack widths is 39% lower and water permeability is 3.1 times lesser than that of HPC, under constant loading. The cracks of HPFRC-CA and HPFRC were completely healed in comparison to 60% for those of the HPC, under a 7-day constant loading and a continuous water flow. HPFRC-CA showed slower self-healing kinetics than that of the HPFRC. However a higher load needs to be exposed in the HPFRC-CA to attain the initial permeability. The samples under SEM imagining showed the existence of ettringite and calcite in the HPFRC whereas the HPFRC-CA showed aragonite. Pazderka[34] investigated the crystalline admixtures and their impact on water proofing properties of concrete. The experiment results revealed that crystalline admixtures have the ability to reduce the water vapour permeability value of concrete around 16%-20%. The complete waterproofing potential was attained only after 12 days of concrete creation

3.5 Self-healing concrete with crystalline admixture and other additives

In recent years, numbers of various cementitious additive materials have been analyzed in the field of self-healing concrete. The enhanced self-healing ability of concretes incorporating of calcium sulfoaluminate based expansive additive (CSA) and crystalline additive (CA) was conducted. The permeability and microstructure of cracked concretes were examined.

The concrete materials with crystalline additive (CA) and calcium sulfoaluminate based expansive additive (CSA) had a favourable surface crack closing ability[28]. A ternary mixture consisting of a blend of Portland cement ,10% CSA and 1.5 wt% CA was an optimal mix design in which the rate of water passing dropped to zero in 28 days, and surface crack width up to 400 μm was completely closed. Investigations with crystalline additive (CA), calcium-sulfoaluminate based expansive additive (CSA) and ordinary Portland cement by Sisomphon and Copuroglu[29] showed the repeatability of self-healing process were completely healed within 28 days. However, smaller cracks were sealed within 14 days. When Jaroenratanapirom and Sahamitmongkol[30] evaluated the mortars constituting various additional cementitious materials such as fly ash, silica fume, and crystalline admixture. It was found that all mortars show self-healing capacity to some extent. For a crack range of 0-0.05 mm width, crystalline admixture (CA) showed the best self-healing performance. When the crack width was larger, silica fume became more effective in self-healing, showing that all mortars were crystal-like materials. Albertini[35] examined the self-healing ability of concrete. The width of crack has a direct influence on the mechanical self-healing capacity of concrete. By increasing the width of crack, the capacity of self-repairing decreases. Self-healing has the effect of improving the durability of the material. The addition of crystalline admixture accelerates the reactions of self-healing and makes the bridges that crystals form between the crack sides stronger. Crystallizing agent increases both self-sealing and self-repairing properties. Compression enhances self-healing. A novel approach has been presented by Al-Kheetan *et al*[35] to add a dual-crystalline hydrophobic admixture in fresh concrete for improving hydrophobicity against chloride and harmful chemicals. The optimum performance was found in mixtures with 2% admixture. Mixture with 2% aqueous hydrophobic admixture revealed marginal strength compared to 2% crystalline cementitious hydrophobic admixture, although water protection appears to be better in cementitious mixture.

3.6 Self-healing of concrete with and without crystalline admixtures

Crystalline additives can also serve as self-healing engineering additions. Crystallization reactions can undergo a delayed activation whenever the material comes back into contact with water or environment moisture. It can happen after crack formation in later ages.

Ferrera *et al*[31] added employed crystalline admixture comprising a mixture of cement, sand and active silica to the raw concrete constituents before mixing. Properties such as stiffness and load-bearing capacity have been estimated by means of 3-point bending tests. The results indicated that underwater immersion crack healed properly. The crystalline additive speed up the crack healing process. Air exposure was not enough to induce any significant recovery.

3.7 Repeatability analysis of self-healing concrete with and without crystalline admixtures

During construction, damage of infrastructure is frequent due to various overloading and changing environmental conditions, and therefore robustness of the self-healing mechanism should concerns in repeatability phenomenon.

Cuenca and Ferrara[37] analyzes the repeatability of autogenous and engineered self-healing in fiber reinforced concrete (FRC) with and without crystalline admixtures. From the obtained results, the following conclusions can be drawn: The highest healing rate was reached for specimens immersed in water, followed by those subjected to dry/wet cycles and by those exposed to open air. For FRC with crystalline admixtures, a general trend was found for all exposure healing conditions in which the crack sealing and healing effectiveness after the 2nd healing was is higher than that after the 1st. It can be reasonably assumed that the crystalline admixture is able to provide a reservoir for delayed hydration reactions over time. This study presents the results from a comprehensive laboratory investigation of the application of 1%, 2% and 8% of crystallizing aqueous and cementitious hydrophobic mineral in fresh concrete. Despite the high slump in the fresh mixture, no segregation was observed in the matured concrete. There was a marginal reduction of strength when a high percentage of admixtures was used. Despite this, significant reduction of water absorption was observed indicating greater hydrophobicity. The optimum performance was found in mixtures with 2% admixture.

Cuenca and Ferrara[41] conducted a study to assess the crack healing effectiveness wherein the specimens were healed for one month and tested again up to a crack width of 0.25 mm (0.01 in.) (cycle after 1st healing). After that, specimens were healed for two months further (2nd healing) and finally, they were cracked once again up to 0.25 mm (0.01 in.). Regarding the repeatability, a general better trend was found for the mix with crystalline admixtures, in which, in addition, the maximum load regain was measured after the 2nd healing cycle rather than after the 1st healing. More recently, Cuenca *et al*[38] attempted to investigate the repeated cracking and healing procedure for one year. The results show that, for the same healing period, the specimens immersed in water reached the largest crack closures. The result of the study showed that the crystalline admixture might favour long-term self-sealing capacity under repeated cracking and healing events.

4 Discussion

The studies shows that each research group applies their own methods of testing.

The present review suggests focusing on autonomous healing by the capsule and vascular-based materials for future research based on two reasons: First, the autogenous self-healing reliability is identified to be lower and secondly, they depend on the composition of the cementitious matrix. Furthermore, these type of healing agents react on contact with air or moisture make them less interesting as premature curing of the agent inside the capsules, and the reaction will not start immediately after release.Reaction to heat is less interesting as it requires human intervention. Therefore the authors choose a second component in the cementitious matrix or a second component provided by additional capsules.

Based on the high performance fibre reinforced cementitious concrete and standard strength concrete, Ferrara and Krelani[24] stated that the mechanical properties have significant effects with some internal chemical pre-stressing of the fibres triggering the expansive reaction of the admixture observed in HPFRCCs and a suitable self-healing indices to quantify the mechanical properties. Joa *et al*[26] studied the mechanical properties of self-healing admixtures exposing to porosity and water absorption capacity with crystalline admixture of 3% by weight. Reddy *et al*[25] replaced cement with silica fume (5%, 10%, 15%) and with the addition of 1.1 % crystalline admixture indicating that all mixtures have a considerable amount of closing ability and strength regain capacity for different exposure conditions. Concrete with 10% silica fumes and 1.1% crystalline admixtures have a 100% strength retrieved capability and complete crack closing ability. Sisomphon *et al*[28] used Calcium sulfoaluminate based expansive additive (CSA) and crystalline additive (CA) in cement-based materials and the mixtures had a favourable surface crack closing ability. The study revealed that water is very essential for self-healing of the cracks. The repeatability test is helpful to analyze the robustness of the self-healing mechanism, chemical admixtures have better repeatability trend in mixing with the concretes, and mechanical recovery is possible even under repetitive preloading.

5 Conclusions

Autogenous healing and free healing have been studied in the current work. The present study mainly focused on the autogenous healing capability of concrete materials with additive geo-materials, simulation and modelling of self-healing phenomenon, engineered cementitious composites' self- healing capacity and finally the conclusion for the admixtures mechanism on the efficiency of self-healing concrete. The review of the various literature revealed that intrinsic self-healing in cementitious materials is capable of extending their service-life. Self-healing concrete saves a lot for the construction industry by reducing the costs of repair and maintenance.

It is hoped by the authors of this work that the information that can be gleaned here may be useful for future researchers in this field. Presently, the application of capsule-based self- recovery systems seems to have promising desirable outcomes for the future construction industry due to its effective features to protection during mixing. However, the vascular healing and intrinsic healing potentials have limitations in movement, curing, abilities, workability and structural coherence.It appears that self-healing concrete is still in its nascent stage. Still, others believe that this type of concrete would be better suited for structures such as tunnels, bridges and highways rather than for houses and buildings. The improvements in the autogenous healing behaviour and mechanical reinforcement properties includes the post-tensioning of cementitious materials by shrinkable polymers which incorporate the nanoclay and polyvinyl alcohol (PVA) fibres using novel techniques. Autogenous healing concrete could optimise if free water that is nanoclay, a critical crack width, fibres control the cracks and right curing environment are available in the mixture. The intrinsic or natural character of cementitious materials has to be taken into explanation in scheming autogenous healing concrete, like a relatively high water-binder ratio and the low efficiency of rehydration of unhydrated cement nuclei. A promising solution to crack repair not only improves the long-term durability and service life, but also ingests the anthropogenic CO_2 emissions, which jeopardise the conditions of earth and is harmful to the life of humans.

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