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Review

Tests and methods of evaluating the self-healing efficiency of concrete: A review

Nasiru Zakari Muhammad [a], Arezou Shafaghat [a], Ali Keyvanfar [a,*], Muhd Zaimi Abd. Majid [a,*], S.K. Ghoshal [b], Seyed Esmaeil Mohammadyan Yasouj [a], Abideen Adekunle Ganiyu [a], Mostafa Samadi Kouchaksaraei [a], Hesam Kamyab [a], Mohammad Mahdi Taheri [c], Mostafa Rezazadeh Shirdar [c], Ronald McCaffer [d]

[a] *UTM Construction Research Centre, Institute for Smart Infrastructure and Innovative Construction, Department of Structure and Materials Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Johor, Malaysia*
[b] *Department of Physics (AOMRG), Faculty of Science, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia*
[c] *Department of Materials, Manufacturing & Industrial Engineering, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Johor, Malaysia*
[d] *Loughborough University, United Kingdom*

HIGHLIGHTS

- Self-healing admixtures used are supplementary cementing materials, polymers and microorganisms.
- Tests at microstructure level are commonly performed to maximize the reliability of the results.
- Self-healing to successful sealing of the crack width is the key issue.
- Visual observation (microscope, digital imaging and camera photographs) are the primary techniques.

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ABSTRACT

To achieve the extended service life of the concrete material, expansive chemicals and microbial induced calcium carbonate precipitation are used, which induced autonomous healing of cracks in concrete. Various approaches are adopted to develop self-healing cement based materials, where experiments are conducted to establish a new method of self-healing. However, comprehensive evaluations of self-healing efficiency are not performed at the level of macro-, micro- and nano scale. Existing approaches evaluated the self-healing efficiency at the macrostructure level. These are based on the durability criterion of water absorption, chloride and acid resistance. Tests at microstructure level are commonly performed to maximize the reliability of the results. Only few tests are conducted at the nanostructure level. It is worth to review all the available tests and methods on self-healing efficiency assessment of cement based materials to develop innovative experimental strategy. Use of supplementary cementing materials, polymers and microorganisms are the most familiar approaches to achieve effective self-healing. Determining the effect of self-healing to successfully sealing the crack width is the key issue. So far, a crack of maximum size of 0.97 mm is healed. Visual observation based on microscope, digital imaging and camera photographs are the primary techniques to assess the width of the filled cracks. Yet, only couple of researches reported on the healing of crack depths of 32 mm and 27.2 mm. Besides, only one report acknowledged the healing of crack length of 5 mm.

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* Corresponding authors.
E-mail addresses: akeyvanfar@utm.my (A. Keyvanfar), mzaimi@utm.my (M.Z. Abd. Majid).

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1. Introduction

Concrete due to availability of its raw materials, affordability, durability and compressive strength is the most widely used construction material. However, a lot of concrete structures including infrastructures inevitably suffer degradation and deterioration over time. This is due to permeation of water which affect the efficiency of the concrete [49]. One of the causes of such deterioration is crack formation at micro and macro levels which create passage for dissolved particles in fluids, unwanted acidic gasses and water ingress. Consequently, these materials and other aggressive substances permeate. Thus, ultimately affect the reinforcement; hence its durability is compromised. Therefore, interaction between concrete and its environment determines its long term performance [12]. In general, water permeation of exposed concrete infrastructure affect durability and also causes corrosion of reinforcing steel bars [9]. Some cracks are not visible and therefore, cannot be accessed. Due to expansion, contraction and permeation of materials, the cracks increase both in size and numbers. For this reason, inspection and maintenance techniques for infrastructure are increasingly drawing attention. Implementation of continuous inspection and maintenance may be difficult especially in the case of large scale infrastructures owing to the huge amount of funds to do it. Some other factors such as location of the damage in the affected structure makes repair difficult. Thus, concept of autonomous repair, otherwise known as self-healing of these dangerous cracks with minimum labour and capital requirements of the affected structures becomes an area of great attraction to researchers. Hence, assessment of self healing efficiency using different approach became attractive due to the requirement of minimum labour and little capital investment. In this regard, self healing efficiency is evaluated using different approach. Self-healing efficiency is the regain in the functionality and desired quality criterion of a cement base material relative to its original form, after healing from crack.

Self-healing materials are those which can restore nearly or all of its original functionality after being damaged, thus, healed completely or partially [27]. Alternatively, self-healing material is that which can detect and autonomically heal damage [13]. In this regard, the healing process proceeds without any manual intervention [26]. Nanotechnology and Biotechnology are relatively the recent advances for the improvement of durability and other concrete properties. The objective of this study is to review all the available approaches for development of self-healing concrete taking into account various tests and methods adopted to evaluate the self-healing efficiency.

2. Literature review of self-healing techniques and measured variable

Cement base materials that have the ability to regain their mechanical properties after crack formation at micro level are the self-healing concrete. Various researchers have studied autogenous self-healing, chemical self-healing and the use of bacteria in the concrete matrix to imitate bone (nature) healing process, thus, produce self-healing concrete material for sustainable development [60]. Expansive materials such as polymers, hollow fibres, mineral admixtures, microencapsulation and microorganisms were used to develop self-healing concrete [88].

According to [73] self-healing could occur naturally by the expansion of hydrated cementitious matrix, calcium carbonate formation, blocking of cracks by impurities present in water and further hydration of unreacted cement. In addition, chemical admixtures, polymers and geo-materials was used to produce self-healing in concrete [20]. Furthermore, calcium carbonate precipitating microorganism were found to induce self-healing in concrete [61,63]. Materials that have expansive characteristics after being introduced into cementitious materials and when combined with mineral additions and or admixtures could improve the self-healing capacity. However, it has to be protected to prevent premature expansion upon reaction with cement in the presence of water.

Parks et al. [53] found that if concrete is made with bulk water containing dissolved salts of Magnesium Silicates and Calcium, it could plug micro-cracks. But, the cracks are not completely healed. They only reduce in size due to a plugging effect. Also efforts have been made to produce some damages in a high strength concrete using tensile preloading. Upon environmental exposure and in the presence of water the artificially simulated crack shows autogenous healing [90]. In this regard, synthetic fibres were introduced into cementitious composite. Consequently, artificially created cracks were successfully healed [50]. Moreover, Van Tittelboom et al. [78] used supplementary cementing materials, to induce an improved self-healing effect of cracks in the concrete at micro level. Such materials, have dual advantages of both the reduction in the cement consumption and also to trigger an enhanced repair of concrete cracks [31]. Also, Ahn et al. [7] figured out, that cementitious composite can be reinforced with high performance fibre. And a better self healing effect than the previous approaches was observed when subjected to different curing regimes. These were the water, sea water and oil water submersions. Though there was self-healing effect, but, only cracks below 50 μm were successfully filled. Hosoda et al. [29] have previously cured, cracked concrete in a continuous water leakage instead of still water. Consequently, an improved self-healing performance was observed. Recently, the efficiency of autogenous healing has been enhanced by post-tensioning of concrete using shrinkable polymer [44]. In this regard, Yıldırım et al. [91] have investigated engineered cementitious material. They found it to be promising self-healing material with an improved self healing performance. Siad et al. [67] have added limestone powder to the engineered cementitious composite. They found that it to substantially recover most of its functionality. Most recently, Pang et al. [14] have investigated the effect of carbonated steel slag as a self healing agent in concrete. The results have shown that, the maximum length and width of the crack healed were 5 mm and 20 μm. Many researchers have adopted visual observation methods to assess the widths of the plugged cracks. In et al. [32] & Wang et al. [82] used ultrasound, light microscope, camera photographs and X-ray computed tomography.

Snoeck et al. [69] have tried to increase service life of concrete structures. They incorporated polymer into the concrete mix to achieve self-healing effect. They obtained a promising result. However, the efficiency depends on the polymer type [20]. Other factors such as polymer dose, type of cement and water-cement ratio affect the efficiency. Polymer was also combined with other materials to improve self-healing efficiency [69]. Some polymer base self healing agent have the potential to induce more than 100% regain in compressive strength [77]. In another study, it has been established that polymer can induce self-healing effect by filling at least 65% of the crack width [28].

Recently, Farhayu et al. [21] & Rahman et al. [57] have all confirmed that, in their study where they reported the regain of flexural strength of 16% more than the control specimen and an increased ultrasonic pulse velocity. Also, [39] have compared different approaches for self healing of concrete. Their finding revealed that self healing of concrete using encapsulation techniques proved to be more promising than the use of super absorbent polymer. This is because; the former can be used for multiple applications as the method does not require water to trigger self healing effect.

Latest advances in the area of nanomaterial has proved to be promising technology that can potentially be used to replicate the natural features in the construction and building materials [59,66]. Recently, nanoparticles were incorporated into the concrete mix to develop new material with a certain desirable characteristics [59]. Nanoparticles, due to their high surface area to volume ratio, final product provides opportunity for extremely great chemical reactivity. Consequently, a new material with a desired property can be produced. Therefore, nanotechnology is used to substantially improve the performance of concrete for the development of sustainable and novel cement based composites. Perez et al. [55] have investigated and established the potential of functionalized silica nanoparticles as a promising material for the development of self-healing concrete. Thus, this area needs further research. The effects of other nanoparticles on durability properties of cement based materials were investigated by Morsy et al. [47]. In the recent days, Muhammad et al. [49] have reported on the use of nanocomposite to enhance waterproof performance of concrete.

Potential of bacteria as a self-healing agent in concrete was investigated [36,18]. This was supported by many other researchers [58,33,76,72]. The application of isolated bacterial cultures and mixed cultures into the fractured concretes were found to seal all the cracks effectively [74]. This was due to precipitation of calcium carbonate caused by metabolic activity of the bacteria [34]. Bacterial culture can be injected into the concrete surface to trigger self-healing [61]. Furthermore, bacterial culture was sprayed on to the surface of a cracked concrete in a parking garage [87]. Consequently, the water permeability was significantly reduced due to self-healing. However, compressive strength was not significantly regained. To offset this limitation, many researches were conducted using microorganism to improve compressive strength and durability properties of cement mortar and concrete [24,80,51,71,68,64,65,45,10,79,23,16,54,42,1,3,5,6]. Compressive strength was further improved when bacteria was used together with admixtures in concrete [5]. Besides, compressive strength was reported to have increased by 36% [4]. Up to now, many researches are still ongoing, where bacteria are being applied in concrete purposefully for more strength and durability improvement [52].

In another investigation, bacteria were directly added to the concrete mix instead of spraying and injection approach. Thus, cracks were plugged following the microbial precipitation due to ureolytic activity of bacteria. This proved to be a better approach. However, harsh environment, within the concrete matrix decreased the life span of the bacteria. As a result, the efficiency of self healing decreased over time [35]. Microbial precipitation depends upon number of factors which include: pH, concentration of calcium ion, Concentration of dissolved inorganic carbon and the presence of nucleation site. Harsh environment within the concrete matrix particularly high alkalinity affect the survival of incorporated bacteria. Thus, need to be protected to increase its life span [11,92]. This protection was achieved by encapsulating the bacteria. It therefore, enhances the self-healing performance of the concrete material. Bang et al. [11] have immobilized bacterial culture within the concrete matrix using polyurethane. Consequently, their life span was extended with the eventual decrease of enzymatic activity (Calcite precipitation). But this, however, stabilizes the enzymatic activity for a long period of time. This was confirm by Wang et al. [83], where they reported 60% regain in compressive strength due to immobilization of bacteria. Irwan and Othman [33] introduced ureolytic bacteria into the concrete matrix. Their activities caused precipitation of calcium carbonate in the crack region with the eventual plugging of the cracks. But, upon immobilization, an improved performance was noted especially at later ages [56]. Furthermore, Wang et al. [84] have encapsulated bacterial spores in a hydrogel before mixing them with concrete. Crack width of 0.5 mm was completely filled. The water absorption was also reduced by 68%. In another investigation, immobilization of bacteria in microcapsule led to a more enhanced performance in which the maximum crack width of 970 μm was completely filled [85]. Most recently, bacteria were encapsulated in graphite nanoplatelets [38]. The result has shown that crack width of 0.81 mm was successfully filled for specimens pre-cracked at 3 and 7 days. The cracks stimulate the release of the healing agent from the capsule. The advantage of nanoplatelets is that they can be thoroughly and evenly distributed within the entire concrete matrix. Consequently, it has caused 9.8% increase of compressive strength. It also has the potential to plug crack that exist at nano level.

In general, materials to be used as healing agents, in the form of capsule must satisfy some requirements such as thermal stability, processing survivability and efficiency in situ rapture for delivery of healing agent. Also De Koster et al. [17] have reported the potential of geopolymer as a possible coating agent for bacteria containing granules. Therefore, it can be successfully applied in concrete as self-healing agent. Meanwhile, the effect of doubled walled sodium silicate microcapsule as a self-healing agent was investigated [48]. It was found to trigger self-healing in the concrete with an impressive performance.

Achal et al. [2] and Mostavi et al. [48] evaluated self healing based on the depth of crack plugged. They have reported plugging of crack depths of 27.2 mm and 32 mm, respectively. All the approaches of concrete self-healing revealed that the encapsulation technique is more effective due to extension of the life span of bacteria for a prolonged performance. And also larger size cracks were completely filled using this technique. Furthermore, a combination of biological and chemical agents proved to be another promising approach for the development of self-healing concrete [46]. In this regard, crack width of 0.22 mm was successfully plugged [70].

3. Implemented approaches for the development of self-healing concrete

Literature clearly revealed that the self-healing in cement-based materials can be obtained by the natural phenomenon or artificial. In the later, filling of cracks is triggered by addition of supplementary cementing materials to the concrete mix or steel fibres. Polymers and microorganisms were also used to mimic

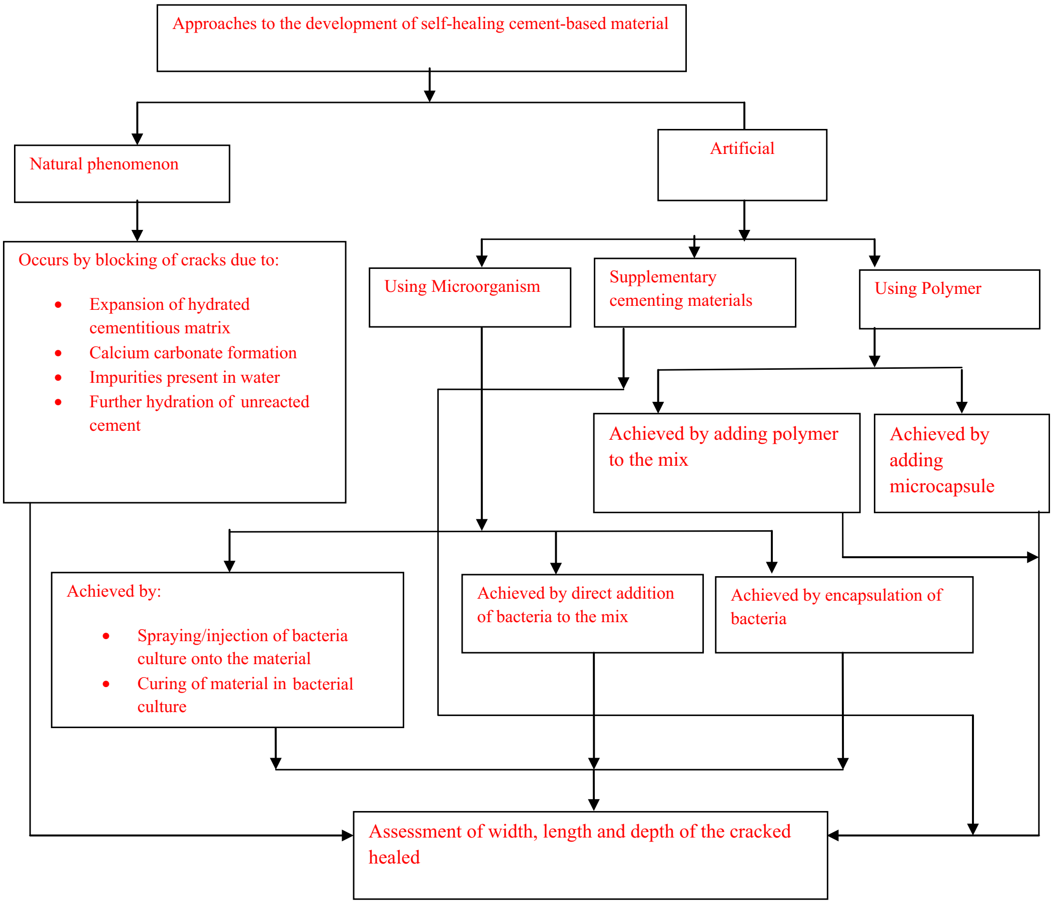

Fig. 1. Taxonomy of cement based self-healing research.

Table 1
Self-healing approach and measured variables.

Approach	Measured variable (width of the crack)	References
Natural	Healing of crack below 60 µm wide was reported	Parks et al. [53], Yang et al. [90]
Supplementary Cementing material	Crack width below 200 µm could be plugged	Huang et al. [31], Van Tittelboom et al. [78]
Polymer	Crack width up to 138 µm was completely filled	Elmoaty and Elmoaty [20], Snoeck et al. [69]
Bacteria and Encapsulation/ Immobilization	Healing of maximum crack width of 0.970 mm was reported	Wang et al. [83], Dong et al. [19], Wang et al. [84,85], Qian et al. [56]
Other (Biological and Chemical)	Healing of crack width up to 0.22 mm was reported	Stuckrath et al. [70]

nature. The width of the cracked healed was assessed using microscope. This is presented in Fig. 1.

4. Self-healing measurement methods

Visual observation using microscope was the predominant method adopted by the majority of the authors to determine the width of sealed cracks [81,22,75]. Digital image, camera photograph with a very high pixel and X-ray computed tomography were among the methods used [41]. Table 1 show that the maximum crack size of 60 µm was filled due to natural phenomenon. Besides, crack width up to 138 µm was completely filled using polymer. Furthermore, the use of Supplementary Cementing material in the concrete mix has caused plugging of 200 µm cracks width. Also progressive improvement in the sealing of larger cracks width of 970 µm was achieved using encapsulation of microorganisms in the preparation of concrete. Yet, this is the most effective approach. Moreover, the use combined chemical and microorganism in the preparation of concrete was reported to have sealed a maximum crack width of 0.22 m.

Based on the available literature to this study, only few researchers by Mostavi et al. [48] and Achal et al. [2] reported the self-healing measurement method based on crack depth filled. Healing of the crack length was also acknowledged by only one research. This is summarized and presented in Table 2 below.

Table 2 displays that the maximum crack depth of 32 mm was filed using encapsulation approach. It has also shown that crack depth of 27.2 mm was filled using microorganism. Therefore, based on the maximum crack width of 0.97 mm and depth of 32 mm plugged as presented in Tables 1 and 2 respectively, it can be said that encapsulation proved to be the most effective amongst all the approaches. Only Pang et al. [14] reported a maximum length of 5 mm of crack plugged.

5. Self-healing measurement methods (independent and control)

In this field, researchers have adopted different tests and methods to establish the efficiency of the self-healing approaches. Crack repairing ability in self-healing process is affected by number of

Table 2
Self-healing techniques and measured variable.

Approach	References	Measured variable (Crack depth and length)
Microencapsulation	Mostavi et al. [48]	Maximum depth of 32 mm crack was successfully filled
Bacteria	Achal et al. [2]	Maximum depth 27.2 mm was successfully filled
Carbonated steel slag	Pang et al. [14]	Maximum length of crack healed was 5 mm

Table 3
Control Variables, Independent variables and Methods.

Control variables	Independent variable	Method	Authors	Results
Free and immobilized organism	Bacteria concentration	Optical density	Bang et al. [11]	More ureolitic activity with immobilized sampled for longer period
Immobilization approach	Dead and living bacteria	Calculating the amount of decomposed urea based on total amount of nitrogen (TAN)	Wang et al. [83]	60% Regain of compressive strength due to immobilization using polyurethane
Laboratory condition	Mix proportion	Weight percent	Chi-wonIn et al. [32]	More self-healing at 35% Slag content
Laboratory condition	Microcapsule dosage	Polymerization	Dong et al. [19]	Increases self-healing
Different bacterial strain	pH	pH Meter	Chahal et al. [16]	High pH resisting strain are more efficient
Bulk water of PH 9.5	Magnesium & Calcium amount	Inductive coupled plasma emission spectroscopy and Inductive coupled mass spectroscopy	Parks et al. [53]	Calcium did not promote self sealing of crack
Laboratory condition	Bacteria concentration	Optical density	Sarkar et al. [62]	More self-healing at optimum concentration
Wet/dry cycles	Amount of polyvinyl alcohol	Weight percent	Snoeck et al. [69]	More self-healing at optimum concentration
Laboratory condition	Amount of super adsorbent polymer	Weight present	Snoeck et al. [69]	More self-healing at optimum concentration
Light weight aggregate	Chemical & Biological agents	Vacuum impregnation	Stuckrath et al. [70]	More self-healing with chemical agent at larger cracks
Laboratory condition	Mix composition	Weight present	Van Tittelboom et al. [78]	Blast furnace slag is more efficient than fly ash
Laboratory condition	Bacteria protection approach	Immobilization	Wang et al. [83]	Polyurethane is more efficient than silica gel
Laboratory condition	Amount of microcapsule	Weight present	Wang et al. [82,84,85]	Bioencapsulated is more efficient than microcapsule alone
Water/air cycle, water high temperature air cycle, submersion in water	Simulated crack width	Tensile preloading	Yang et al. [90]	Immersion in water produced more self-healing
Microfibers	Different type of super absorbent polymer (SAP)	Weight present	Snoeck et al. [69]	SAP type B can plug cracks of up to 138 μm completely
Medium cultures	Different bacterial strains	Liner method	Talaiekhozani et al. [74]	Mix culture of bacterial strains was able to plug cracks. However, compressive strength was not significantly regain
Ambient conditions	Microcapsule sizes	Particle size analysis	Dong et al. [19]	More self healing with microcapsule of 230 μm size
Curing regimes of ambient conditions, high humidity and water immersion,, 50 mm long glass capsule and 6.15 mm diameter	Different mineral compounds	Encapsulation	Kanellopoulos et al. [37]	More healing effect for water curing using Sodium silicate and Colloidal silica
Laboratory condition	Direct and Indirect addition of bacteria	Immobilization by different carriers	Khaliq and Ehsan [38]	More self-healing effect with an increase of compressive strength by 9.8% using immobilization by graphite nano platelets than both light weight aggregate immobilization and direct addition also crack width up to 0.81 mm was healed
Curing conditions, w/c of 0.3	Amount of microcapsule	Weight percent	Li et al. [40]	The best result was obtained at water curing and 2% content of microcapsule
Curing condition,	Simulated crack width	Preloading	Luo et al. [43]	Efficiency of self-healing decrease with increase of crack width and which was limited to 0.80 mm
w/c of 0.48	Amount of epoxy	Weight percent	Farhayu et al. [21]	Self-healing is more effective at 10% epoxy content
w/c 0f 0.48	Amount of epoxy	Weight percent	Rahman et al. [57]	Significant recovery of compressive strength at 10% epoxy resin
Laboratory condition	Protection and direct addition of bio-reagent	Encapsulation	Wang et al. [82]	Encapsulated bacteria is more effective in plugging larger size cracks
Bio and non bio-microcapsule	Amount of microcapsule	Weight percent	Wang et al. [85]	Bio-microcapsule is more effective in plugging as large size crack
Laboratory condition	Type of aggregate	Batching by weight	Pang et al. [14]	More self healing using carbonated steel slag than normal aggregate. Maximum length of the rack healed was 5 mm

factors. Common influencing factors were the crack width, curing regime and cracking age [43]. Other influencing variables based on the available literature were summarized and presented in Table 3. Table 3 demonstrates the control and independent variables, methods for measuring the independent variables and the results obtained by different authors. As can be seen from Table 3, increase of the concentration of bacteria in the concrete mix causes more precipitation of calcium carbonate, hence more self-healing either with free or immobilized organisms. Likewise self-healing increases with increase of polymer dosage. For the natural self-healing, using bulk water containing salts of calcium and magnesium, it has been revealed that only the later was found to promote self-healing. Table 3 has also shown that water curing was more efficient when engineered cementations concrete was subjected to different curing regimes. Furthermore, it has shown that, chemical agent, plays more effective role in self-healing than biological agent, when each of the two is separately added to the concrete mix. Bio encapsulation is also more efficient than the use of micro-capsule alone. The Table has also shown that, comparing different curing regimes, water curing approach was better than air and moisture curing in terms of self-healing. It can as well seen from the table that healing efficiency decreases with increase of crack width. Table 3 has further shown that only one research by Khaliq and Ehsan [38] reported on the application of nano based material in this area of research. They found that compressive strength was increased by 9.8%. Their investigation has also shown that a crack width up to 0.81 mm was successfully plugged.

6. Structure tests for evaluating self-healing efficiency

Structure tests conducted at macro, micro, and nano scale levels are used to establish the quality criterion of concrete in hardened form. These include macrostructure, microstructure, and nanostructure tests. Self-healing efficiency is evaluated based on such tests as presented in Table 4. Thus, it regained the functionality and desired quality criterion of a cement based material relative to its original form after healing from crack. Literature hinted that all the researchers evaluated the self-healing efficiency by conducting tests at macrostructure scale. Several of them have conducted microstructure test to maximize the reliability of their results. However, very few authors carried out test at nanostructure level

6.1. Macrostructure tests

Regarding the efficiency of self-healing, several tests at macro scale were conducted. Table 4 enlists the common tests those are conducted to regain the compressive, flexural strengths, and other mechanical properties [40]. These include split tensile and toughness tests [42,15]. Other tests are the water permeability, ultrasonic pulse velocity as reported by many authors [19,62,86,8]. Some authors have further conducted sorptivity and gas permeability tests to determine the self-healing efficiency of encapsulated sodium silicate, colloidal silica and tetraethyl orthosilicate [37]. It is acknowledged that sorptivity and gas permeability were reduced by 18% and 69%, respectively. Granger and Loukili [25] conducted stiffness test to evaluate the performance of the healed material. Farhayu et al. [21] reported that the flexural strength of the healed concrete is 50% higher than the control specimen. Snoeck et al. [69] performed thermo gravimetric analysis to identify the white deposited material within the crack. Porosity and pore size distribution test, chloride penetration and oxygen profile tests are among the test conducted by many other researches as summarized in Table 4.

It is established that the compressive strength can be regained up to 60% after self-healing. Furthermore, ultrasonic pulse velocity

Table 4
Macro, Micro and Nano Structure Tests.

Tests	Dependent variable	Standard methods	Best results	Authors
Permeability and Mechanical properties	Sprptivity, chloride penetration, porosity, Ultrasonic Pulse Velocity, Chloride permeability Flexural and Compressive strength, Gas permeability, split tensile, Stiffness Test	Liquid methanol RILEM 25 PEM (II-6), ASTM C1585, MIP, ASTM C1202, JSCE-G571-2003. RILEM CEMBUREU	18% decrease in sorptivity, 69% decrease in gas permeability, Increase of compressive strength by 9.8%, 60% regain of compressive strength, decrease in water permeability by 68%, regain of compressive strength at 40% more than the control specimen, 12% improvement of compressive strength faster recovery in the global stiffness than control sample	Kanellopoulos et al. [37], Khaliq and Ehsan [38], Wang et al. [83,85], Achal et al. [2], Farhayu et al. [21], Siad et al. [67], Van Tittelboom [92], Sarkar et al. [62], Li et al. [40], Luhar and Gourav [42], Cao et al. [15], Dong et al. [19], Aldea et al. [8], Granger and Loukili [25]
SEM, XRD, EDS	Fabric of Nano structure of Concrete	Not specified	Significant improvement on some method used, mainly from optimum hydration rate	Chahal et al. [16], Van Tittelboom et al. [39], Dong et al. [19], Parks et al. [53], Sarkar et al. [62], Huang and Ye [30], Bekas et al. [13], Junker and Schlangen [36], Wang et al. [86]
Nano-structure measurement	Nano-mechanical value	Nano indentation	20% increase of nano mechanical values of transition zone. (Interface between concrete and the deposited material) compared to the deposited layer	Xu and Yao [89]

Table 5
Scale of structural tests conducted using various approaches for evaluation of self-efficiency.

Tests conducted	Scale of test	References
Ultrasonic Pulse Velocity, Compressive strength, Flexural, Toughness, stiffness	Macrostructure test only	Bang et al. [11], Talaiekhozani et al. [74], Elmoaty and [20], Yang et al. [90], In et al. [32], Cao et al. [15], Nishiwaki et al. [50], Xu and Yao [89], [71], Mostavi et al. [48], Yıldırım et al. [91]
Water permeability, Chloride permeability, sulphate, compressive strength, ultrasonic pulse velocity, water absorption,	Macrostructure and Durability tests	Aldea et al. [8], Van Tittelboom et al. [78], Wang et al. [83], Snoeck et al. [69], Dong et al. [19], Sangadji et al. [61], Wang et al. [82], Sarkar et al. [62], Yıldırım et al. [91]
Porosity, Compressive strength, Chloride permeability, rapid chloride penetration, Water absorption, SEM,	Macrostructure, Microstructure and Durability tests	Aldea et al. [8], Parks et al. [53], Achal et al. [3], Achal et al. [2], Wang et al. [84], Siad et al. [67]
Water absorption	Microscopic and Durability tests	Snoeck et al. [69], Feiteira et al. [22], Wang et al. [84]
Visual observation	Microscopic tests	Hosoda et al. [29], Virginie and Junker [81]
esem, xrd, sem	Microscopic and Microstructure tests	Ahn et al. [7], Liu et al. [41], Luo et al. [43], Pang et al. [14]
Stiffness test, flexural test	Microscopic and Macrostructure tests	Granger and Loukili [25]
Flexural, tensile splitting, Air permeability, eds, ftir, fesem, xrd	Macrostructure and Microstructure tests	Huang and Ye [30], Stuckrath et al. [70], Farhayu et al. [21], Rahman et al. [57], Khaliq and Ehsan [38]
Water absorption, Capillary coefficient, Sorptivity, gas permeability, chloride diffusion, ftir, xrd, sem	Microstructure and durability tests	Parks et al. [53], Wang et al. [83], Li et al. [40], Kanellopoulos et al. [37]
Water permeation coefficient, coefficient of capillary suction, thawing/freezing	Durability tests	Qian et al. [56], Wikto and Jonkers [87]
Flrxural, upv, nanoscale mechanical measurement	Macrostructure and Nanostructure tests	Xu and Yao [89]

is found to increase after self-healing. Therefore, based on the test results presented in Table 4, durability criterion with more critical effects over long period of time could hence be addressed using biological self-healing approach. This will extend of life span of concrete infrastructure. However, other important tests such as bonding strength between the deposited materials within the cracks and the concrete itself, stress–strain relationship curve, and gas permeability tests are seldom addressed. Thus, it is essential to evaluate the development of self healing concrete using various approaches. Consequently, this will allow a better comparison of bonding capacity of the deposited material within the racks and compatibility with concrete composition.

6.2. Microstructure

Generally, these tests are conducted at micro scale to identify and characterize the deposited materials within concrete cracks after self healing. It maximizes the reliability of the results obtained. Due to this reason, most of the researchers are conducted the tests such as the Scanning Electron Microscope (SEM), Field Emission Scanning Electron Microscope (FESEM), and X-ray diffraction (XRD). Scanning electron microscope is used to identify the morphology of the deposited materials within the cracks [30]. These materials are the calcium carbonate precipitation by different bacterial strains, hydration product as well as polymerized products. Most recently, self-healing performance is assessed using Raman spectroscopy [13]. Table 4 displays the SEM, XRD and EDS results. In this way, the reliability of using bacteria as a self-healing agent in concrete is maximized [36,86]. Moreover, the results obtained using micro structures confirmed the deposition of these irregular crystals within the cracks of the test samples. Thus, water absorption, chloride permeability and acid ingress are substantially decreased together with the increase of signal transmission rate of ultrasonic pulse velocity

6.3. Nanostructure tests

These tests are performed at nano scale to further maximize the reliability of the test results. Recently, Xu and Yao [89] evaluated the efficiency of self-healing using nanostructure test. It is found that the average nano mechanical values of the transition zone are 20% more than that of the outer precipitates, which served as strong bond between the concrete matrix and deposited layer (Table 4).

It is worth to conduct tests at both macro and nano scale to determine the bonding strength at the interface between the deposited materials and the substrate (cement based material) within the cracks. This will add to the reliability of the process.

7. Comparison of assessment tests

Table 5 enlists various tests that are performed using different approaches. It is evident that majority of the researchers are focused only on the macro mechanical properties to evaluate the self-healing efficiency. In addition to the durability tests some researchers determined the macrostructure properties as a better approach. Several others evaluated the efficiency at macro and micro scale level together with durability tests. These appeared more reliable approach than the previous one. Few researchers conducted the durability tests after observing the crack width using microscope, however with less reliability. The next less intense approach adopted by other authors is the use of microscope only. Microstructure test in addition to microscopic observation are often conducted to achieve more reliable result. Table 5 clearly indicates that very few researchers used the microscopic and macro mechanical tests for self-healing determination. The efficiency of self-healing is evaluated by conducting macrostructure and microstructure tests. Some conducted microstructure test in addition to durability tests. Another least reliable approach is the evaluation of self-healing efficiency using durability tests only. Two researchers (Table 5) evaluated the self-healing efficiency by conducting tests at nano scale. Inclusive literature review hinted that no researchers evaluated the self-healing using durability test, macro mechanical test, microstructure test, and nanostructure test simultaneously. It is suggested that future research must develop a combined approach to establish more reliable way of evaluating self-healing efficiency.

8. Conclusion

Present study analyzed and compared several tests and methods that were developed to evaluate the self-healing efficiency of concrete. Bio and/or chemical deposition of calcium carbonate or polymerization products were mainly triggered by the presence of moisture, high humidity and water. However, the water curing condition proved to be the most effective in terms of self-healing [40] and [37]

a) Based on the previous studies, common approaches to development of self-healing concrete were the use of biological and polymer as well as biological and chemical agents respectively. Some authors have tried using supplementary cementing materials while recently, the use nano-based materials as self healing agents was recently reported by only one research. Thus, more researches using nano-based materials need to be carried out. Also, among the available approaches, encapsulation/immobilization of bacteria proved to be more effective in sealing millimetre size cracks up to 0.97 mm wide and 32 mm depth. Furthermore, use of carbonated steel slag aggregate led to autogenous healing of 5 mm crack length.
b) Self-healing was measured in terms of decrease in the crack width and depth via visual observation using microscope and digital imaging, camera photograph and X-ray computed tomography.
c) Recovery of mechanical properties was the common test adopted by majority of the authors to evaluate self-healing efficiency. Other authors have further conducted tests at macro and microstructure scale to maximize the reliability of the results. Moreover, very few authors have conducted tests at nano structure scale. However, durability, macro mechanical, microstructure as well as nano scale level tests respectively have so far not reported to have conducted in the same experiment by any of the authors.
d) Researches on the use of fungi to heal the concrete is still lacking.

It can be observed that methods of measuring self-healing efficiency of concrete are not well standardized. Followings are shortcoming of available methods based literature conducted:

- Lack to initiate definition of self-healing efficiency.
- Lack of availability of standard procedure or main referenced procedure to measure rate of self-healing.
- Lack of adequate research on the length of the healed crack.
- Lack of adequate research on the depth of cracked healed.
- Lack to report the volume of crack healed.
- Lack to report the speed of crack healing.
- Lack to address the speed dynamic of crack healing versus concrete age.
- Lack to address the structural crack healing.
- Lack to address the durability of crack healing versus concrete age.
- Lack of any quantitative data on the bonding strength between the concrete and the deposited material within the crack.

The above are presented based on authors observation while future research will be highlighting more. This is while the trend to initiate new way of self-healing method is increasing and establishment of a self-healing efficiency is basic on success of future researchers.

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