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Invited paper

Robust Self-Healing Concrete for Sustainable Infrastructure

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Abstract

This article introduces the concept of self-healing concrete for sustainable infrastructure through reduction of maintenance and repair in the use phase. To realize this goal, self-healing must observe at least six robustness criteria – long shelf life, pervasive, quality, reliable, versatile, and repeatable. Five broad categories of self-healing approaches, namely chemical encapsulation, bacterial encapsulation, mineral admixtures, chemical in glass tubing, and intrinsic healing with self-controlled tight crack width, are evaluated against the robustness criteria. It is suggested that while significant progress has been made over the last decade in laboratory studies, important knowledge gaps must be filled in all categories of self-healing approaches to attain the goal of smart sustainable infrastructures that possess self-repair capability in the field.

1. Introduction

Many developed countries, including Germany, S. Korea, and the US, are experiencing unprecedented amounts of civil infrastructure deterioration, so much so that the annual outlay for repair and rehabilitation has outstripped the cost of new infrastructure construction. The annual economic impact associated with maintaining, repairing, or replacing deteriorating structures is estimated at $18-21 billion in the U.S. alone (Vision 2020 2006). The American Society of Civil Engineers estimates that $2.2 trillion is needed over the next five years for repair and retrofit; a cost of $2 trillion has been estimated for Asia's infrastructure. To make matters worse, repairs of concrete structures are often short-lived. In the US, it is estimated that half of all field repairs fail and require re-repairs (Mather and Warner 2003). The concerns related to civil infrastructure deterioration are not limited to the economic cost of repair and rehabilitation, but extend to social and environmental costs. While there is little documentation and quantification of the social and environmental costs, it is generally agreed that repeated repairs of civil infrastructure over their service life is decidedly unsustainable.

Over the last decade, the concept of concrete infrastructure able to repair itself without human intervention has emerged as a possible cure for overcoming civil infrastructure deterioration. While the idea remains a novelty in practice, it has attracted a significant amount of attention in the research community. Many different approaches to functionalizing concrete to possess self-healing ability have been investigated. Given that damage in concrete is dominated by cracks, much attention has been given to self-repair of cracks. In a few cases, field trials have been launched. These studies hold promise to the feasibility of future civil infrastructure smart enough to detect its own damage and undergo repair by itself. Thus self-healing concrete has significant implications in extending service life, and reducing economic, social and environmental costs of civil infrastructure. That is, self-healing concrete could be a major enabling technology towards sustainable civil infrastructure.

Figure 1 shows the number of publications related to self-healing concrete over the last decade. It paints a picture that we have entered into an intense phase of research on the development of self-healing concrete, and the pace of research will likely continue to accelerate. A survey of the literature indicates that this development is spread over the major continents, and is particularly intense in Europe and Japan.

There have been a number of review articles on self-healing concrete [see, e.g. Wu *et al*. 2012, RILEM TC-

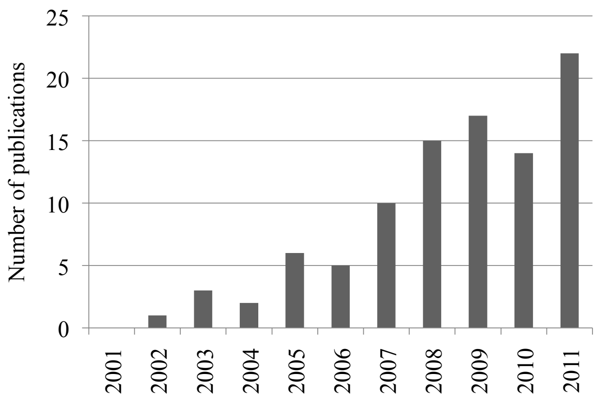

Fig. 1 Archived journal publications on self-healing concrete over the last decade (2001-2011) (Source: Google Scholar on-line)

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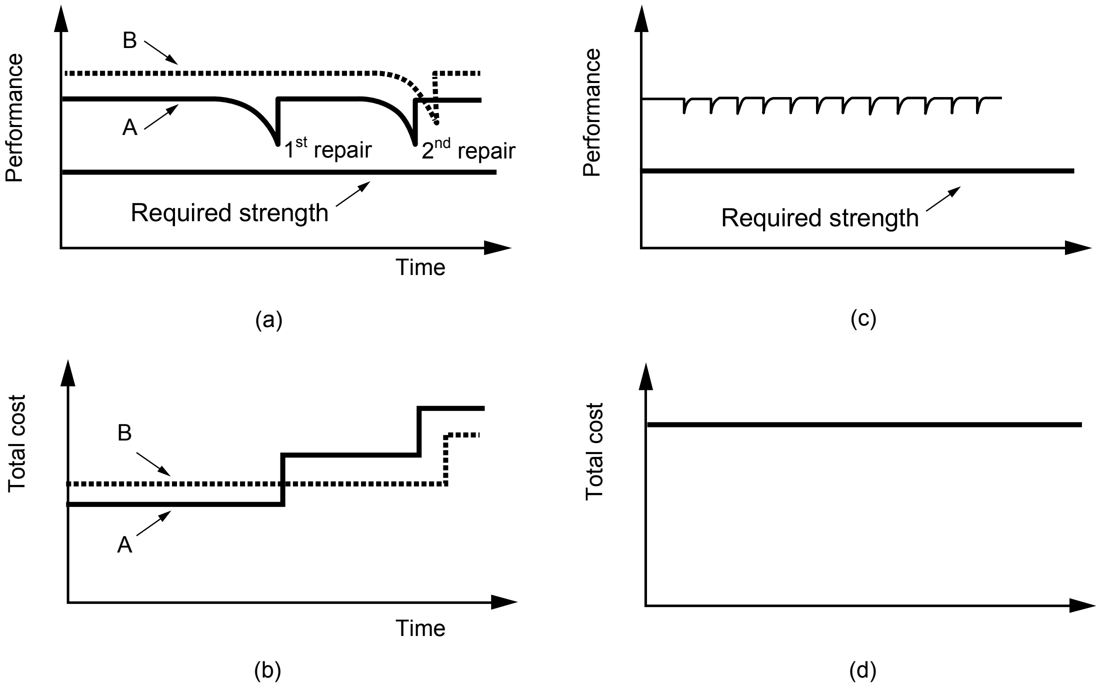


Fig. 2 (a) and (b): Conceptual life-cycle cost model emphasizing cost increase associated with repair events for conventional concrete structure; The dotted lines are for a higher performance higher cost concrete B compared with concrete A; (c) and (d): Corresponding life-cycle cost and performance when self-healing is included (van Breugel, 2007).

221-SHC STAR]. The purpose of the present article is not to repeat these reviews, but rather to propose the concept of *robust* self-healing – a set of robustness criteria against which several generic self-healing approaches can be evaluated. As such, the literatures referenced are not meant to be exhaustive of what has been published. The objective of such an evaluation is aimed at highlighting advantages and limitations of various self-healing approaches, to spur additional research to overcome current limitations, and to generally accelerate convergence of concrete technology developments that support the realization of smart sustainable infrastructure systems with self-repair functionality. The robustness criteria serve as a filter for self-healing approaches under study in laboratories and identify those that are likely effective in infrastructure damage self-repair in the field.

2. Impact of self-healing on infrastructure life cycle cost

Some direct benefits of concrete self-healing include the reduction of the rate of deterioration, extension of service life, and reduction of repair frequency and cost over the life cycle of a concrete infrastructure. These direct benefits may be expected to lead to enhanced environmental sustainability since fewer repairs implies lower rate of material resource usage and reduction in energy consumption and pollutant emission in material production and transport, as well as that associated with traffic alterations in transportation infrastructure during repair/reconstruction events.

Van Breugel (2007) suggested a conceptual life cycle performance and cost model. The current practice of periods of gradual infrastructure deterioration punctuated by discrete repair events leads to increasingly high cumulative costs that may match or even exceed the initial construction cost (**Fig. 2a,b**). In contrast, infrastructure built with self-healing concrete may have higher initial cost, but the self-healing functionality maintains the quality of infrastructure with minimum or no additional cost accumulation over the life cycle, resulting in a life-cycle cost that could be competitive with that of current concrete infrastructure (**Fig. 2c,d**).

A simple quantitative life cycle cost model was proposed by Li *et al.* (2010) for reinforced concrete infrastructure subjected to a chloride environment. The service life and life cycle cost analysis framework is depicted in **Fig. 3**. Using a reinforced concrete bridge deck as illustration, the service life is assumed to be governed by the time to corrosion initiation t_i of steel reinforcing bars as influenced by the rate of chloride diffusion through the cover concrete, and corrosion propagation t_p as influenced by the spalling propensity of the concrete cover. Life-365 software (Life-365, 2012) was used to compute the service life and life cycle cost. In this model experimental data for chloride diffusion coefficient in cracked concrete serve as the input parameter in Life-365.

The presence of self-healing alters the crack pattern, reducing the crack width (lower right corner box in **Fig. 3**). Complete sealing is assumed to take place when concrete cracks are limited to below 30 μm, as has been experimentally demonstrated (Yang *et al.* 2009). This

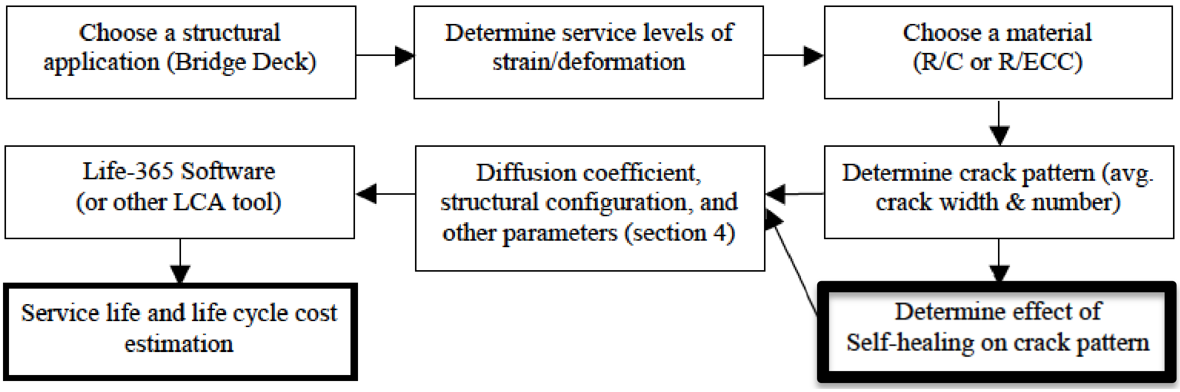


Fig. 3 Service life and life cycle cost estimation framework accounting for self-healing functionality in concrete (Li *et al*, 2010).

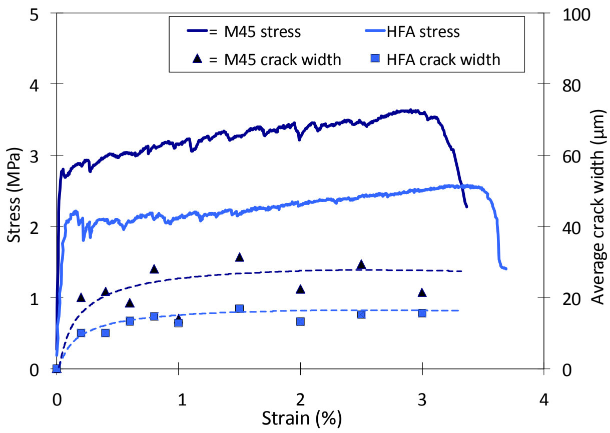


Fig. 4 Tensile Stress-Strain Curve and Crack width Development of Two ECCs. Tight crack width can be designed down to below 20 μm, even at tensile strain exceeding 2%.

results in a lowering of the chloride diffusion coefficient that forms the input to Life-365 that computes the lengthened service life and reduction in life cycle cost.

The realization of tight crack width for self-healing was achieved in Engineered Cementitious Composite (ECC) (Li *et al*. 2002; Li 2003). ECC exhibits tensile strain hardening with strain capacity of several percent. During strain hardening, multiple microcracking takes place with crack width limited to below 60 μm. Typical tensile stress-strain curves and crack width development in ECC are shown in **Fig. 4**.

The measured effective diffusion coefficient D_e for ECC was found to increase linearly (Sahmaran *et al*. 2007) with imposed tensile strain (**Fig. 5a**). For normal concrete, the measured effective diffusion coefficient was found to increase exponentially with tensile deformation. In terms of crack width, the diffusion coefficient was found to scale parabolically as shown in **Fig. 5b**. For ECC, the linear increase in D_e was due to increase in crack number while the crack width remains essentially fixed even as deformation increases to a large value (**Fig. 4**).

For comparison with ECC with an imposed strain of 0.3% (concrete fractures at 0.01%), a normal concrete

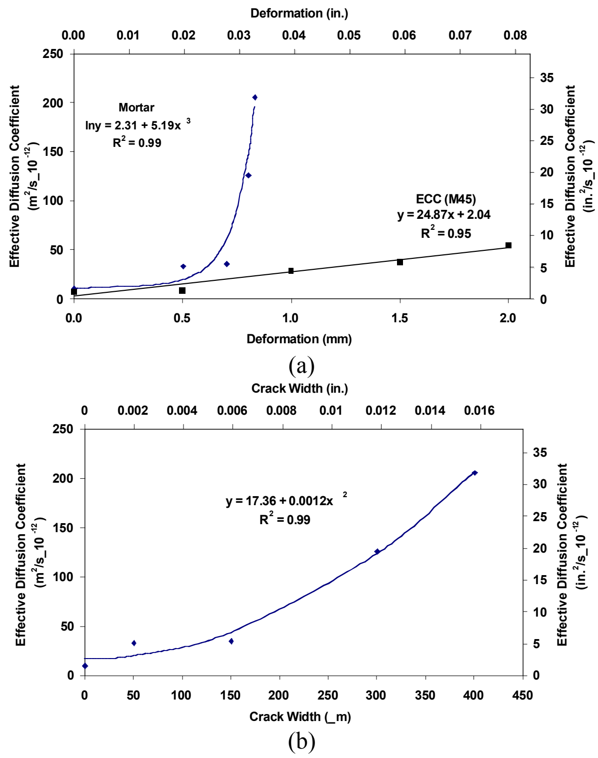
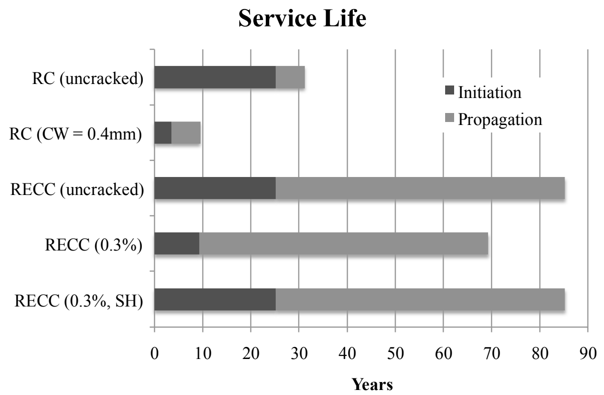


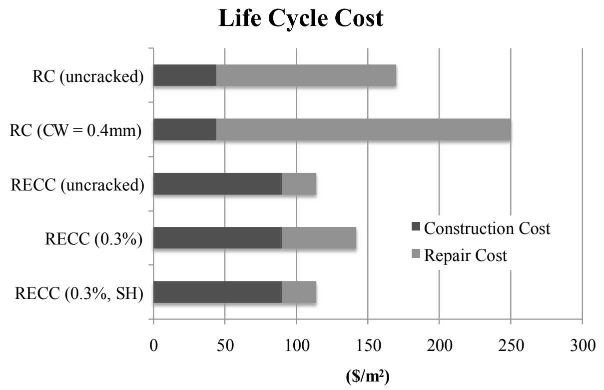
Fig. 5 Chloride Diffusion Coefficient (a) as a function of specimen flexural deformation in mortar and ECC and (b) as a function of crack width for mortar (after Sahmaran et al 2007). These experimental data are used to compute the service life and life cycle cost (Figure 3).

with crack width up to 400 μm (allowable by AASHTO for exterior exposure, AASHTO 2004) was adopted in the study on service life and life cycle cost by Li *et al.* (2010). A high chloride exposure (0.75% weight concentration on concrete surface) on a bridge deck located in Detroit, MI was specified. A corrosion inhibitor of 15 liter/m^3 was further assumed. (Other imposed deformation values and corrosion inhibitor values were also analyzed, but the main conclusions remained essentially the same.)

The computed service life is summarized in **Fig. 6a**. The presence of inhibitor increases the time to corrosion



(a)



(b)

Fig. 6 Computed (a) service life and (b) life-cycle cost showing the effect of self-healing (Li et al, 2010). The "construction cost" here refers to mainly the initial material cost.

initiation t_i for uncracked concrete from 8.9 years to 25.2 years. However, t_i drops to 3.5 years when a crack of 400 μm width is introduced. For the case of ECC, t_i drops from 25.2 years to 9.3 years when a tensile strain of 0.3% is imposed but fully recovers to 25.2 years when self-healing takes place and completely seals the microcracks. The time to corrosion propagation of six years in normal concrete is extended to 60 years in ECC based on its strain-hardening ability. ECC is able to withstand the tension induced by steel rebar expansion as a result of corrosion, thus suppressing the spalling of the concrete cover (Lepech 2006). Through a combination of tensile ductility and self-healing ability, the total service life of the ECC bridge deck was shown to extend from less than ten years for the RC deck to over eighty years.

The calculated life-cycle costs (including materials cost and repair cost) for these cases are shown in **Fig. 6b**. Life-365 computes a life cycle cost of $170/m^2 for R/C when uncracked, but increases to $250/m^2 when a crack of 400 μm width is present. For the ECC bridge deck, the material cost assumed is higher ($90/m^2 compared with $44/m^2 for normal concrete) reflecting the additional costs in ECC due to inclusion of fibers and other expensive ingredients. However, the repair cost for the ECC deck drops from $206/m^2 for a concrete deck with 400 μm cracks to only $52/m^2 for a ECC deck with imposed 0.3% strain, and further down to $24/m^2 when self-healing takes place. Thus, despite the higher initial material (construction) cost, the ECC bridge deck ends up with a lower life cycle cost of $114/m^2, compared with $250/m^2 for the RC deck with 0.4 mm crack width.

The above calculations highlight the economic value of self-healing for civil infrastructure. Self-healing translates into sealing of microcracks that reduces the effective diffusion coefficient for chloride ion transport, which in turn translates into longer corrosion initiation time and extended service life before repair is needed. Although the numerical values are based on a bridge deck in Michigan with focus on steel corrosion deterioration, the general model framework demonstrates the potentially significant economic impact of concrete with self-healing functionality.

The life cycle cost model described above is helpful in estimating service life extension and economic savings from reduced repair due to self-healing in concrete infrastructure. To assess the reduction of environmental and social impacts, a more comprehensive life-cycle assessment model is needed. The infrastructure sustainability framework (**Fig. 7a**) proposed by Keoleian *et al.* (2005) may be extended for this purpose. Input and output parameters are computed for each life cycle phase as shown in **Fig. 7b**. The self-healing functionality could be embedded into the module that quantifies life-cycle major and minor repair and maintenance events in the use phase, much as what has been described above for the life cycle cost model. In this way, the return loopings indicated by "Repair and maintenance" in **Fig. 7b** are reduced. This more comprehensive model will allow additional evaluation of sustainability metrics such as global warming potential, primary energy consumption, and motorist lost time associated with reconstruction events, in addition to agency costs. This research is being carried out at the University of Michigan.

3. Robustness of self-healing

To realize the goals of infrastructure sustainability highlighted above, it will be necessary to move beyond demonstrating the *feasibility* of self-healing in concrete. Self-healing will need to meet at least the following six criteria to assure robustness of this functionality and its intended purpose in real structures. Apart from quantifying self-healing robustness, these six criteria can also be used to evaluate the advantages and limitations of various approaches to achieving self-healing in concrete infrastructures.

3.1 Six criteria for robustness

Shelf life: Unlike many manufactured products, civil

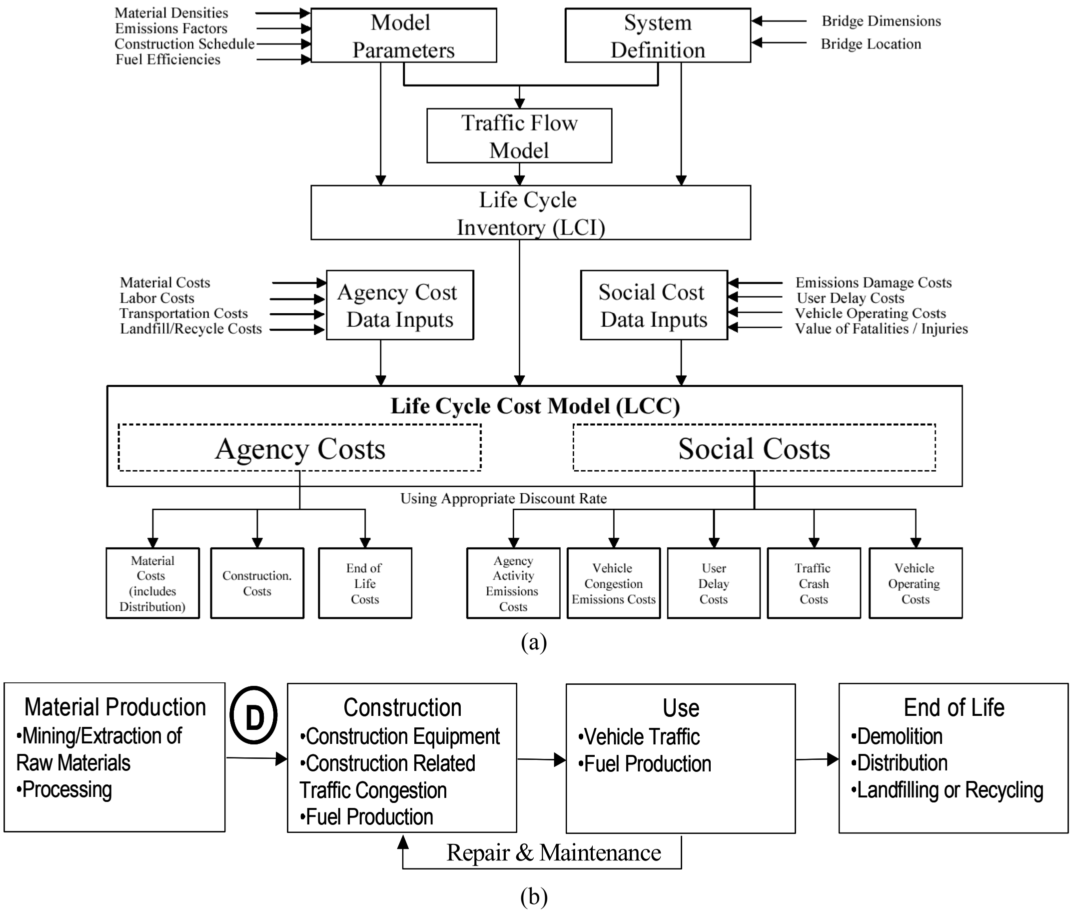


Fig. 7 (a) Integrated LCA-LCC Model (Keoleian et al 2005). Self-healing impacts on the infrastructure repair frequency and associated economic and environmental costs during the use phase of a life-cycle and reduces the loop back shown in (b).

infrastructure has a relatively long service life ranging from fifty to a hundred years. Since it is impossible to predict when damage of the concrete will occur over this period of time, it implies that any self-healing functionality must also possess a shelf life of fifty to a hundred years. This long shelf life requirement for infrastructure applications is possibly unique among engineered materials and products. This criterion indicates that the self-healing process, whether physical, biological, chemical or a combination of these, must possess a shelf-life that is as long as the design life of civil infrastructure.

Pervasiveness: Since most civil infrastructure experiences complex combined environmental and mechanical loading, it is prudent to assume that damage of the concrete may occur anywhere in the structure and that crack orientation may be difficult to predict accurately. This assumption implies that the self-healing functionality needs to be pervasive in the structure, rather than being available only in limited and discrete parts of a structural component. Cracks should be rehealed regardless of actual orientation.

Quality: Ideally, self-healing should lead to full recovery of both transport and mechanical properties. Transport properties include permeability and diffusivity, while mechanical properties include stiffness, strengths and possibly ductility. If only transport properties are recovered, then the self-healing functionality is truly limited to self-sealing only. The percentage of recovery for a given level of damage also provides an indicator of the quality of healing. The quality criterion implies that the self-healing process must lead to products that not only fill the cracks, but also chemically bind the crack faces together.

Reliability: Self-healing reliability refers to the consistency of mechanical and/or transport property recovery. A lack of consistency from test to test (large coefficient of variation) would suggest the lack of reliability of the particular self-healing approach.

Versatility: Civil infrastructure is exposed to a variety of environments, some continuously dry, others continuously wet, and still others experience periods of dryness and wetness. They may also be exposed to a high chloride environment, such as bridge decks and roadways in northern climates where deicing salts are used, or in coastal regions where the infrastructure may come into contact with salt from seawater. Self-healing approaches that allow recovery of material properties in widely varying environments would be considered highly versatile.

Repeatability: Damage in a given civil infrastructure will likely take place repeatedly due to multiple overload events over the lifetime of the structure. Self-healing approaches should therefore be able to function not just once, but multiple times over the design life of the structure. This criterion implies that the self-healing mechanism must remain operational when cracking occurs multiple times, even possibly in the same location of the structure.

The above six criteria – *Shelf life, Pervasiveness, Quality, Reliability, Versatility, and Repeatability* – may be used to evaluate the robustness of any given self-healing approach. In most cases, current available experimental data are inadequate to conduct a quantitative evaluation. However, qualitative considerations of these six criteria with respect to current knowledge on the various self-healing approaches should still be useful to identify advantages and potential shortcomings that may require additional research efforts. This will be carried out in Section 3.3 after describing five generic approaches for self-healing.

3.2 Self-healing approaches

Self-healing approaches may be broadly grouped into five categories – chemical encapsulation, bacterial encapsulation, mineral admixtures, chemical in glass tubing, and intrinsic self-healing with self-controlled tight crack width. These approaches are schematically illustrated in **Fig. 8**. Related approaches that require human intervention, such as applying heat, are not considered here.

Chemical encapsulation (**Fig. 8a**) includes all approaches that utilize self-healing chemical agents contained in microcapsules that are dispersed uniformly in the concrete. While different chemicals and microcapsule materials have been investigated, the common

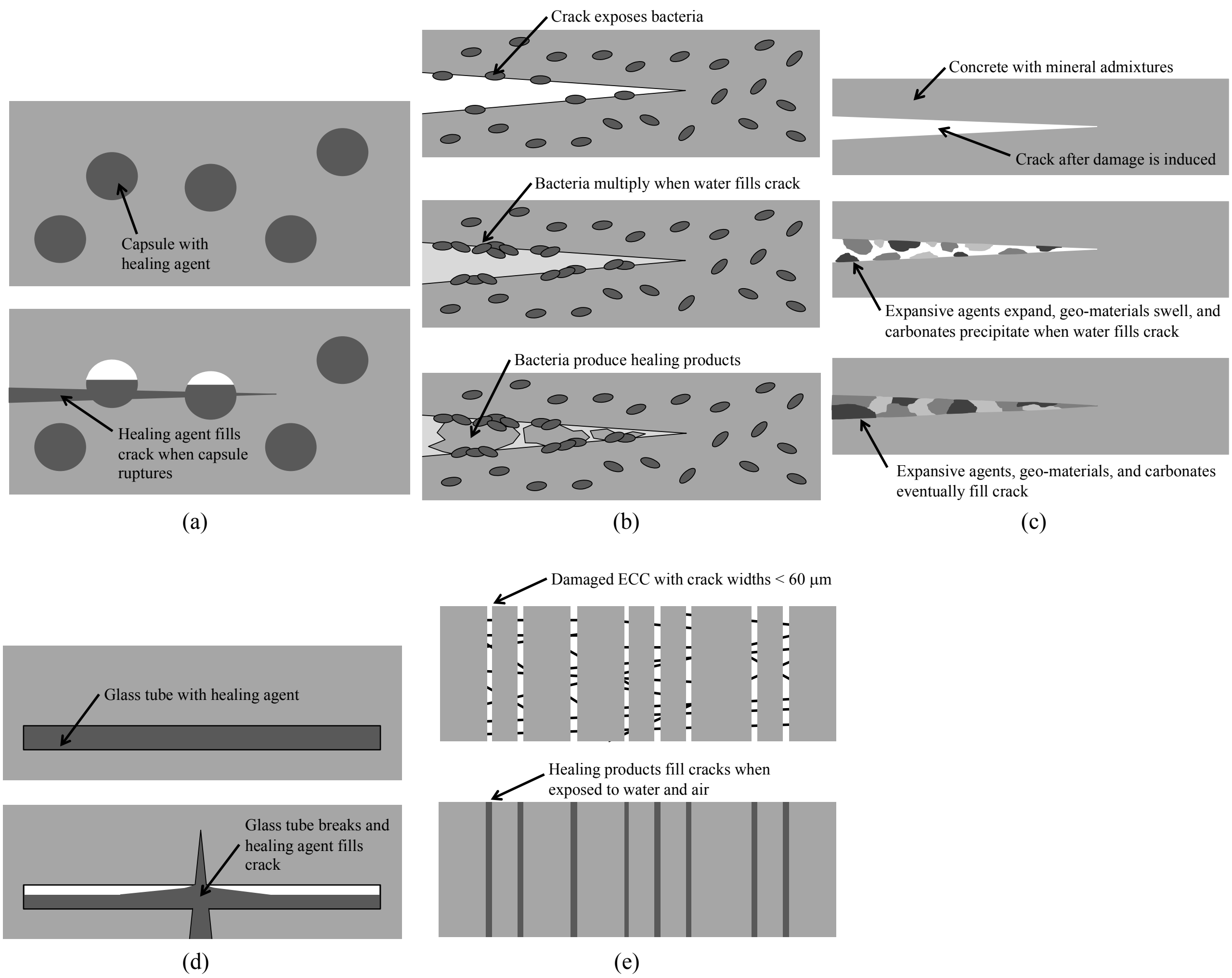


Fig. 8 Schematic illustration of (a) chemical encapsulation self-healing approach, (b) bacteria additive self-healing approach, (c) mineral admixtures self-healing approach, (d) glass tubing self-healing approach, (e) self-controlled tight crack width self-healing approach.

theme is to isolate the healing chemical(s) from the concrete by the microcapsules until a concrete crack breaks them open. Leaking of the chemicals then either seals the crack and/or bonds the crack faces.

This approach is appealing due to the versatility of microencapsulation technology that can essentially encapsulate a variety of chemicals in any size down to submicron size. Huang and Ye (2011), for example, employed sodium silicate solution encapsulated in 5 mm wax capsules for self-healing in a cementitious composite which demonstrated recovery of mechanical properties including flexural stiffness and strength after damage induced by three-point bending tests.

The bacteria additive self-healing approach utilizes bacteria that induce precipitation of calcium carbonate as a result of carbonate generation by bacteria metabolism in a high calcium environment (**Fig. 8b**). The specific bacteria chosen must be able to withstand the high alkalinity of cement and the internal compressive pressure as microstructure continuously densifies with cement hydration. A nutrient must also be available to feed the bacteria. For example, Jonkers (2011) encapsulated spores of *Bacillus pseudofirmus* and *Bacillus cohnii*, calcium lactate and yeast extract in porous expanded clay particles up to 4mm in size. Evidence of self-healing was based on visual observation of calcium carbonate precipitates on the cracked surfaces after 100 days of immersion in water (Wiktor and Jonkers 2011). Wang *et al*. (2012) immobilized *Bacillus sphaericus* in silica gel and polyurethane inside 40 mm long glass tubes with 3mm in diameter. Release of the bacteria upon glass tube fracturing caused by a mortar crack allows breaking down of urea into ammonium (NH_4^+) and carbonate (CO_3^{2-}). In the high calcium environment, calcium carbonate is precipitated on the bacterial cell wall and in the surrounding medium. Regaining of flexural strength and reduction of water permeability coefficient was reported as evidence of rehealing.

Mineral admixtures have been deployed as an approach for self-sealing of concrete cracks by reducing the water permeability after concrete damage (**Fig. 8c**). Kishi and co-workers (2007) demonstrated the use of a tailored mix of expansive agents ($C_4A_3\bar{S}$, $CaSO_4$, and CaO), swelling geo-materials (mainly silicon dioxide and sodium aluminum silicate hydroxide, and montmorillonite clay) and various types of carbonates as partial (10% by weight) cement replacement, and found that the sealing action can be effective for cracks up to 0.22mm in water permeability tests in concrete with normal w/c ratio. Self-sealing phenomenon of cracks was confirmed by time-lapse optical microscopy, SEM and X-ray mapping on the rehealed crack zone, and by use of water permeability test under immersed condition (Ahn *et al*. 2010). The combined effects of geo-material swelling upon rehydration, expansive agent expansion and precipitation of carbonates in the crack were suggested as the mechanisms leading to effective (speedy formation and chemically stable healing products) healing. Calcium sulfoaluminate (CSA) has also been utilized (Hosoda *et al*. 2007; Kishi *et al*. 2007; Sisomphon *et al*. 2011; Sisomphon and Copuroglu 2011) as an expansive agent for self-sealing.

The use of glass tubing for self-healing is based on the concept of self-sensing and actuation when a concrete crack is intercepted by the glass tubing which reacts by fracturing and releasing a repair chemical (**Fig. 8d**). (It should be noted, however, that this sensing-actuation concept is in fact present implicitly or explicitly in all five self-healing approaches discussed here.) Indeed the glass tubing approach may be considered a variant of chemical encapsulation as an alternative form of healing agent delivery approach, with the advantage of potentially carrying a larger amount of healing agent compared with microcapsules. Various chemicals including methyl methacrylate (Dry and McMillan 1996), ethyl cyanoacrylate (Li *et al*. 1998; Joseph *et al*. 2010) and polyurethane combined with an accelerator (van Tittelboom *et al*. 2011) have demonstrated the ability of recovering concrete mechanical and transport properties. These chemicals are chosen to have low viscosity so that the healing agents can leak from the fractured glass tube into the concrete crack to perform the self-healing. As noted above, the healing agent is not limited to chemicals, but could be biological (Wang *et al*. 2012). Evidence of self-healing was based on mechanical reloading of beam elements that show a rebound of stiffness and/or strength (Li *et al*. 1998; Joseph *et al*. 2010; Van Tittelboom *et al*. 2011) and a reduction of permeability coefficient (Van Tittelboom *et al*. 2011).

One of the simplest approaches utilizes the intrinsic natural tendencies of continued hydration, pozzolanic, and carbonation processes when cracks in cementitious materials are exposed to water and carbon dioxide (in air), taking advantage of the existence of unhydrated cement grains and fly ash in a binder with low water/binder ratio. This approach can only work if the cracks are tight, 100 μm or less. ter Heide and Schlangen (2007) demonstrated this approach by continued hydration of damaged concrete specimens placed under water and subjected to a compressive load that closes the cracks. Li and co-workers demonstrated the ability of self-healing in ECC that tensile strain-hardens with crack widths self-controlled to below 50 μm (**Fig. 8e**). This tight crack width remains even when the material is loaded to several percent tensile strain. Evidence of self-sealing in ECC has been demonstrated by reduced permeability over time (Lepech and Li 2009). Evidence of self-healing in the mechanical sense has been demonstrated by recovery of stiffness in pre-damaged specimens (Sahmaran and Li 2008; Yang *et al*. 2009; Yamamoto *et al*. 2010; Li and Li 2011) exposed to various environments.

3.3 Self-healing robustness of various approaches

In this section, the five broad categories of self-healing approaches will be evaluated against the six criteria summarized in 3.1 above. **Table 1** highlights the essence of the evaluation results. In performing this evaluation, it is realized that the current literature does not contain adequate data sets for proper assessment of reliability, as it has been typical that only a small number of specimens are used in all self-healing investigations so far.

As previously stated, chemical encapsulation is appealing due to its versatility. Not only can the capsules incorporate a variety of healing agents and be made in any size, but this approach could be used in a variety of infrastructures since the healing process is independent of the external environment. This approach also has the potential of a long shelf life, although this would depend on the chemical being encapsulated and how long it can remain active. Chemical encapsulation is also pervasive since the capsules could be mixed directly into concrete, provided they are strong enough to withstand the mixing process, thus making them uniformly dispersed in the matrix without being damaged. Huang and Ye (2011) demonstrated that this approach can be used to regain mechanical properties such as flexural stiffness and strength, but no work has been carried out to determine the recovery of transport properties. Also, although no studies have been conducted with more than one loading cycle, healing by chemical encapsulation is likely not repeatable since the capsules would be emptied during the first damage cycle unless repeated crack opening in the rehealed zone can be avoided.

Bacterial encapsulation has been used to completely regain transport properties in damaged concrete specimens (Jonkers 2011), but the regain in mechanical properties appears minimal (Wang *et al*. 2012). With this approach, the shelf life is determined by how long the bacterial spores are able to remain viable within the concrete matrix. Jonkers (2011) showed that encapsulated spores are viable for at least six months, and currently running viability tests will determine if there is a loss of viability over longer periods of time. This technique is also pervasive if the bacterial spores are incorporated into capsules that can be mixed directly into the concrete matrix. Currently it is unclear if the bacterial encapsulation self-healing approach possesses versatil-

Table 1 Robustness matrix of self-healing approaches.

	Chemical Encapsulation	**Bacterial Encapsulation**	**Mineral Admixtures**	**Chemical in Glass Tubing**	**Intrinsic Healing with Self-Controlled Tight Crack Width**
Shelf Life	Potential of long shelf life; would depend on healing agent in capsule	Currently running viability tests show spores are viable for at least 6 months	Long shelf life as long as additives remain reactive and unhydrated	Potential of long shelf life; depends on healing agent used	Long shelf life since no special additives are incorporated into ECC for self-healing
Pervasive	Yes, capsules could be dispersed uniformly in concrete	Yes, capsules containing spores could be dispersed uniformly in concrete	Yes, admixtures are mixed in and dispersed uniformly in concrete	No, tubes have to be placed in discrete locations where cracks and crack orientation are anticipated	Yes, intrinsic healing mechanisms available anywhere in the structure for any crack orientation
Quality	Regains mechanical properties to an extent; self-sealing has not been investigated	Complete self-sealing demonstrated; regain of mechanical properties is minimal	Capable of complete self-sealing; regain of mechanical properties has not been investigated	Self sealing and regain of mechanical properties occur to an extent, but not 100% efficient	Self-sealing and regain of mechanical properties can be 100% efficient
Reliable	Inadequate data for proper assessment	Inadequate data for proper assessment	Inadequate data for proper assessment	Inadequate data for proper assessment	Inadequate data for proper assessment
Versatile	Yes, healing mechanism is independent of external environment	Currently limited to continuous water exposure	Currently limited to continuous water exposure	Yes, healing mechanism is independent of external environment	Yes, demonstrated feasible in a variety of exposure environments
Repeatable	No studies have been done with more than one loading cycle; likely not repeatable	No studies have been done with more than one loading cycle	No studies have been done with more than one loading cycle	Not repeatable	Yes, partial regain in stiffness for samples exposed to more than one loading cycle

ity or repeatability characteristics since all studies to date are carried out under continuous water exposure, and no repeat loading has been applied. While experiments by Wiktor and Jonkers (2011) found that cracks up to 0.46 millimeters can be completely sealed with healing products, the versatility of this approach may be limited if the bacterial spores lose viability under drying conditions. Still, the bacterial encapsulation approach may be suitable for self-sealing of underground or water containing structures where continuous exposure of the concrete to water may be expected.

Self-healing using mineral admixtures is highly pervasive since the additives are used as partial cement replacements and are therefore dispersed uniformly throughout the concrete. Visual observation and permeability tests have shown that this approach allows for complete regain of transport properties (Kishi *et al.* 2007; Hosoda *et al.* 2007; Sisomphon *et al.* 2011; Sisomphon and Copuroglu 2011), but no research has been carried out to determine the feasibility of regain of mechanical properties. Currently it is unclear if this approach is versatile or repeatable; no investigation has been performed to determine the repeatability of this method and samples have only been allowed to heal in continuously wet environments. The mineral admixture self-healing approach appears to be intended for underground structures. The continuously wet environment for such structures would be inductive for this self-healing technique. No specific work has been conducted to determine the shelf life, but there is potential for a long shelf life as long as sufficient mineral admixture particles remain unhydrated and reactive.

The main advantage of the glass tubing approach is that this technique can be quite versatile since the healing mechanism is independent of the external environment. Joseph and co-workers (2010) found that specimen age did not affect the healing response. Therefore, this approach could also provide a healing mechanism with a long shelf life, but this would depend on the healing agent used. The use of glass tubing is not pervasive since the tubes have to be placed in discrete locations where cracking is anticipated. In addition, the glass tubing must be oriented in a direction close to perpendicular to the anticipated crack path, so that the concrete crack would break the glass tube to activate the healing mechanism. Also, this technique is not repeatable since the glass tubes would most likely be emptied during the first loading cycle. It has been shown that self-healing using this approach leads to recovery of both transport and mechanical properties, however, it is not 100% efficient and the healing under repeated damage was minimal (Li *et al.* 1998; Joseph *et al.* 2010; Van Tittelboom *et al.* 2011).

Utilizing the intrinsic self-healing tendency of cementitious materials coupled with self-controlled tight crack width of ECC has proven to be a promising approach. Although no specific experiments have been conducted to determine the shelf life of this approach, it is likely that there would be a long shelf life since the intrinsic mechanisms of continuing hydration, pozzolanic reaction and carbonation in cementitious materials are known to be long lasting. This technique is highly pervasive since it utilizes unhydrated cement and fly ash, which are uniformly dispersed within the cementitious matrix. It has been found that the recovery of transport and mechanical properties can be 100% efficient depending on the preloading levels and exposure conditions (Lepech and Li 2009; Sahmaran and Li 2008; Yang *et al.* 2009; Yamamoto *et al.* 2010; Li and Li 2011). It has also been shown that this approach can be repeatable. Yamamoto *et al* (2010) found that there is a regain in stiffness for samples exposed to multiple damage and rehealing cycles. ECC self-healing has been demonstrated under continuous or intermittent water exposures, and at room and elevated temperatures (Yang *et al.* 2009) and at young and mature ages (Yang *et al.* 2009; Yang *et al.* 2011). In addition, ECC has been shown to self-heal under various adverse conditions, such as highly alkaline and chloride environments (Sahmaran and Li 2008; Li and Li 2011).

4. Field studies on self-healing ECC

Limited research has been conducted to determine the level of self-healing under field conditions. Although self-healing in the lab may look promising, these results have limited value unless the self-healing techniques discussed above can be applied to structures in the field.

Kishi *et al* (2011) conducted field tests to determine the recovery of water tightness due to self-healing in water-retaining containers. The concrete, which contained mineral admixtures for self-healing, was prepared in a ready-mix concrete plant and delivered to the casting site in an agitator truck. The concrete was then cast into box shaped water-retaining containers and, after several months of curing, cracks of 0.2 millimeters were induced and the boxes were filled with water. The amount of water leakage over time was measured to determine the extent of self-healing. It was found that the fresh properties of the self-healing concrete produced at the ready-mix plant satisfied construction field requirements and the mineral admixtures within the concrete helped seal the cracks and reduce water leakage from the containers.

Herbert and Li (2011) performed a three-month study on the self-healing of ECC in the natural environment, where samples were exposed to random and sometimes extreme environmental conditions. Through visual observation, it was found that the majority of cracks less than 20 micrometers in width underwent self-healing. In contrast, cracks up to 150 micrometers have been able to heal under controlled laboratory conditions (Yang *et al.* 2009). It was also found that ECC samples in the natural environment were able to recover a significant portion of their initial stiffness after three months of natural environment exposure, but this recovery was less than that for samples healed in the laboratory. Therefore, although self-healing of ECC in the natural environment is promising, it is not as robust as the self-healing seen under controlled laboratory conditions.

5. Further discussions and conclusions

From a holistic viewpoint, the recent technological developments in self-healing concrete and the serious deterioration of civil infrastructure on a broad scale produce a convergence of technology push and pull that should result in future smart infrastructure with the intrinsic ability to self-heal when damaged. The success of this new technology will transform the current civil infrastructure practice of deterioration-repair cycles to one of health self-maintenance without external intervention such as inspection and repair. The implication of self-healing infrastructure on economic impact, environmental sustainability, and quality of life is expected to be significant.

All five self-healing approaches – chemical encapsulation, bacterial encapsulation, mineral admixtures, chemical in glass tubing, and intrinsic healing with self-controlled tight crack width, have been demonstrated to be effective to some extent under certain laboratory conditions. However, there are limitations in almost all approaches that will require additional investigation before the vision of truly self-repairing civil infrastructure can be fully realized. In some cases, the limitations are intrinsic to the fundamental nature of the self-healing approach so as to make it impossible to attain robustness.

For the chemical encapsulation approach, almost all the robustness criteria could be met in principle, although substantial additional research will be needed to verify this expectation quantitatively. A significant advantage of this approach is the continuing maturation of technology for micro-encapsulation of a wide range of chemicals for self-healing (see, e.g. Yang *et al.* 2008). Perhaps the most severe limitation is the difficulty in meeting the repeatability criterion since once emptied, the capsules are not likely to be usable for repair during the next cycle of damage. This may imply that self-healing can take place just once for damage in the same location of a structure. On the other hand, if the microcapsules are truly on the size-scale comparable to cement grains, then there may be enough of them to persist in self-healing functionality even under multiple damage events. The challenge would be to assure filling the crack volume given the limited amount of healing chemicals that could be encapsulated in such microcapsules especially in light of mm-size cracks commonly observed in concrete infrastructure.

For the bacterial encapsulation approach, the adoption of biological processes for concrete self-healing could be highly efficient and attractive. However, it is not known if the bacterial spores are able to remain viable during the entire service life of civil infrastructure, especially if the structure is not under a constantly wet environment. These considerations of shelf life and versatility may limit the applicability of this approach to certain types of structures such as underground or water retaining infrastructure.

For the mineral admixtures approach, demonstration of the effectiveness of sealing cracks and reducing water leakage has been highly convincing. An outstanding feature of this approach is the ability to self-heal cracks of relatively large width, up to 0.22 mm. This is one of the few approaches that have undergone limited field-testing (Kishi *et al.* 2011). The most urgent research needs here include the verification of true self-healing in the sense of recovery of mechanical properties to levels seen before concrete damage, and verifying that rehealing under repeated damage is feasible.

For the chemical in glass tubing approach, the demonstration of mechanical property recovery and the flexibility of adopting different types of self-healing chemicals in the glass tube make it promising. The strongest limitations, however, are the non-pervasiveness of this approach unless a network of such tubes is used throughout the structure. The fracturing of the glass tube to activate the self-healing mechanism also limits the repeatability of this approach. Glass tubes and capsules are simply different geometric forms of vessels containing the repair agent. As microencapsulation technology continues to mature, it is likely that the limitations of the glass tubing approach would yield to the advantages of microencapsulation.

The intrinsic healing with self-controlled tight crack width approach (based on ECC) shows promise of meeting all six robustness criteria. However, the economic cost of ECC is at present substantially higher (two to three times) than that of normal concrete. As shown in Section 2, the higher initial cost of ECC could be offset by the lower life-cycle maintenance cost, so that this self-healing approach could be justified on an economic life cycle cost basis. In addition, the tight crack width and tensile ductility of ECC serves other purposes of infrastructure durability and resiliency enhancements.

It may be of interest to investigate combinations of the five different approaches to lead to further enhancements in self-healing. Already, encapsulation methods have been used for both chemicals and bacteria. In future, it is conceivable that highly robust self-healing could be attained by combining bacteria and/or expansive additives in ECC with tight crack width control.

The lack of data to properly evaluate the reliability of the various self-healing approaches points to the need for further research with a larger number of specimens.

Perhaps the biggest adversary of self-healing is large crack width. As a tension-softening material, normal concrete is difficult to reheal since the crack width can extend indefinitely. Even with steel reinforcement, it is generally agreed that crack width in concrete structures is difficult to control. This point is driven home by the change in code language between the 1995 edition (ACI 318R-95) and the 2002 edition (ACI 318R-02) of the ACI Building Code. The specification (in the 1995 edition) of the Gergely-Lutz "z" factor in steel reinforcement for limiting the crack width to a recommended value of 400 μm for exterior exposure conditions was removed. In its place was the specification in the 2002 edition of maximum reinforcement spacing "intended to limit surface cracks to a width that is generally acceptable in practice but may vary widely in a given structure". As crack width increases, the efficiency of self-healing drops rapidly. ECC has definite advantage in attaining higher self-healing efficiency by virtue of intrinsic tight crack width control in the material, without dependence on steel reinforcement.

As pointed out in Section 4, very little work has been conducted in self-healing under a natural environment. Conditions in the field such as highly variable temperature and precipitation may render self-healing that looks promising under highly controlled conditions in the laboratory meaningless. This is an area of research that should receive much more attention in the future, if the objective is to realize extended service life and to reduce economic, social and environmental life-cycle costs for civil infrastructure. Given the trajectory of research and progress made over the last decade, self-healing sustainable concrete infrastructure appears to be a realistic expectation in the recent future provided that the six self-healing robustness criteria are met with additional research and validated under field conditions.

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