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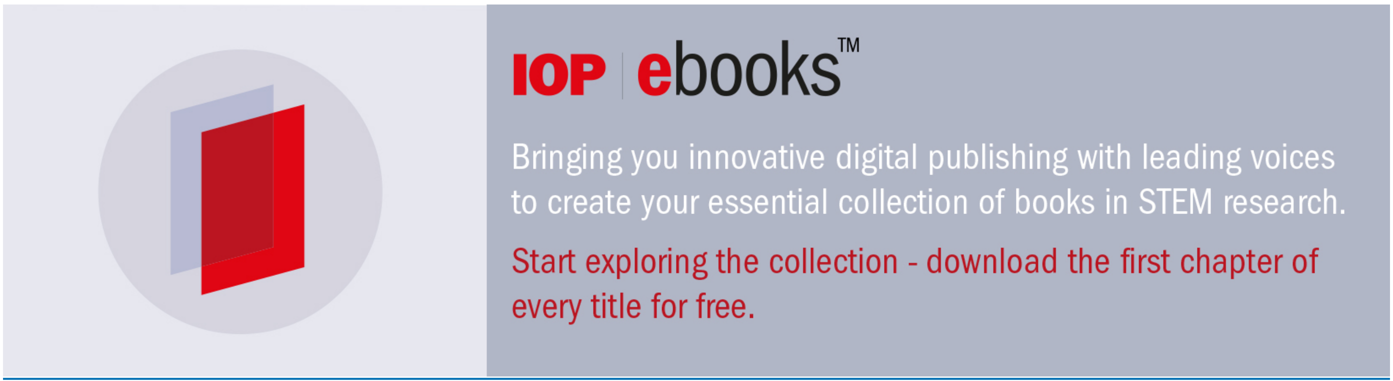

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Self-healing cement-based materials: an asset for sustainable construction industry

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Abstract. Worldwide increasing consciousness for sustainable use of natural resources has made “overcoming the apparent contradictory requirements of cost and performance effectiveness a challenging task” as well as a major concern. Self-healing cement-based materials, by controlling and repairing cracks, could prevent “permeation of driving factors for deterioration”, thus extending the structure service life, and even provide partial recovery of the engineering properties relevant to the application. This paper will outline the current state of art on self-healing cement-based materials and experimental methods for the assessment of the self-healing capacity. Moreover, it will also critically analyse the current hindrances which challenge the engineering community in paving the way towards the reliable and consistent incorporation of self-healing concepts and effects into a durability-based design framework for buildings and structures made of or retrofitted with self- healing concrete and cementitious composites.

Keywords: self -healing; advanced cement based materials; experimental methods; durability-based design

1. Introduction

According to a survey recently published by the WEF, the construction industry accounts for about 6% of global GDP (from 5% in developed countries up to 8% in developing ones) with total annual revenues of about 10 trillion USD and 3.6 trillion USD added values, such figures are expected to increase to an estimated 15 trillion USD revenues by 2025 [1]. Construction industry, which currently directly employs more than 100 million people worldwide, serves all the industry verticals, with 38% of global construction volume accounted for by residential housing, 32% by transport, energy and water infrastructures, 18% by institutional and commercial buildings and 13% by industrial sites. The importance of the construction industry, for countries to enjoy an inclusive and sustainable growth, has been further highlighted by a quite recent (2014) estimate, that for an extra 1% GDP investment in infrastructures, in advanced economies, a 1.5% GDP increase after four years can be expected [1,2].

The construction industry is also the single largest global consumer of resources and raw materials and generator of solid waste as well. For example, about 40% of solid waste in the US and 35% in EU28 countries (Eurostat 2014 estimate) derives from construction and demolition activities [1].

In this global framework, concrete plays a role of paramount importance, with about 10 billion tons (corresponding to about 4 billion cubic meters) produced each year. This makes it not only the second largest used material worldwide, the first being water, but also correspond to twice as much than the total of all other building materials, including steel, wood, aluminum and plastic. The production and consumption of such large quantities of concrete feeds the deman0d on the one hand for a likewise huge production of cement, which has overcome 4 billion tons/year, with continuous increase even in the worst years of the financial crisis, and, on the other hand, for the consumption of aggregates, with a demand of about 48 billion tons in 2015, as well as of water.

The production of cement as well requires large quantities of raw materials (approximately about 2 tons of limestone and shale per ton of cement), and high energy (about 4 GJ per ton of cement) and produces about 1 ton CO_2 per ton of cement, which makes the cement industry responsible of about 5% not energy related greenhouse gas emissions worldwide.

These figures anyway have not to be deceptive and misleading about the carbon footprint of concrete as a construction material, since “the reason concrete has a high footprint as a whole is that there are just such huge concrete quantities used”, and the reason for which it is used in such large amounts and “has been used in […] pioneering architectural feats for millennia” is that “it is, simply, a remarkably goof building material” and “is in fact a very low impact material” [3]. Besides the well-known and likewise appreciated good performance of concrete in terms of, among the others, compressive strength, thermal inertia and cost effectiveness, what makes it a low impact material is the worldwide local availability of its raw constituents, including cement, which can be nowadays regarded as a global commodity. This implies that “if you replace concrete with another material, it would have a bigger carbon footprint” [3].

In this framework it well worth remarking that both cement and concrete industry are really making giant leaps forward in improving their sustainability signature. The adopted measures range from optimization of cement production processes, including, *e.g.*, reuse of waste heat or use of secondary fuels such as waste tires in cement kilns, to peculiar and nowadays consolidated practices in concrete technology which encompass the use of supplementary cementitious materials, as replacement of cement in concrete and in the production of multi-blended cements, to the use of recycled aggregates, originated from construction and demolition wastes, as a replacement of natural ones, up to the use of treated waste water and even sea water in the mix-design [4].

Concepts and figures exposed above do actually refer to the sustainability signature of the material “per se” and to its production process. A thorough evaluation of the sustainability of a construction work, in the framework of the built environment as a whole, has anyway to consider the performance of the construction in service conditions all along its life cycle, including its durability.

The durability of (reinforced) concrete structures is, as of today, one of the major concerns, if not the most dramatically serious one, of the construction industry. Reinforced concrete structures more and more frequently exhibit earlier and faster and more and more severe decay of their level of performance in the service scenarios and conditions they have been supposedly designed for.

Though a comprehensive analysis of the causes of the aforementioned problem is so far lacking, several issues can be called for to justify the somewhat premature decay of structural performance and anyway their higher durability sensitiveness, including, *e.g.*:

- the fact that current construction technologies, and in some cases the same structure concept, and the qualification of the workmanship have not adequately paced up with the development in material concept and technology of concrete and cement-based materials;
- climate change and environment pollution issues, together with the fact that the material and design concept together have pushed ahead the service stress boundaries, are going to threaten more severely the material, when in service in the structure.

It has also always to be borne in mind that, because of its inherent brittleness and low tensile strength, concrete is expected to crack and is generally used in combination with, prevalently steel, reinforcement, which takes the tensile forces generated by the applied actions. Cracks open an ingress pathway for aggressive agents to penetrate inside a structural element, reaching the reinforcement and the inside bulk concrete, and activating complex degradation mechanisms, among which the corrosion of the same reinforcement is surely among the most threatening ones. Unexpected and/or not correctly predicted decay of the structural performance results into unpredicted maintenance needs which, besides being costlier than if correctly predicted and planned, hardly can restore the pristine level of performance, thus implying also an increased frequency of the subsequent following maintenance actions and an uncontrolled growth of the life cycle costs. Recent estimates have shown that, *e.g.*, the cost of repairing corrosion damages (including also automotive and aircraft industry) sums up to about 3.5% of the world GDP [5] and that currently a significant share of the year budget of construction industry in developed countries accounts for maintenance and repair of existing structures. At the same time, the lifespan of the same maintenance and repair works is dramatically shortening, as from a case history analysis recently provided by the CON-REP-NET project [6], which has shown that 50% of the repaired concrete works failed again, 25% of which in the first 5 years after repair. A percentage share which increases to 75% and 95% respectively if the time observation frame is extended to 10 and 15 years after the repair.

A true "durability based" design approach is actually far from being formulated in current design codes, though it is appropriately recognized that the achievement of the required durability is the complex outcome of the suitable choice of structure concept and shape, material selection, as well as of the enforcement of "operational" design criteria, which limit the crack width under the anticipated actions to suitable scenario-based threshold values [7,8].

Limitation of crack width being hence recognized as the major requisite for the intended durability, concrete technology has developed, over the past fifty years, Fiber Reinforced Concrete (FRC). Thanks to the dispersed fiber reinforcement, an effective control of crack width can be achieved throughout the entire structure and starting from the very early ages. As a matter of fact, because of their wire-like features, fibers are able to interact with cracks much fines than what obtainable with the smallest commercially available bar diameters [9]. The boundaries of this concept have been pushed forward up to the formulation of the so-called High Performance Fiber Reinforced Cementitious Composites (HPFRCCs), whose composition is designed through micro-mechanical concepts based on fiber pull-out and crack tip toughness balance. Thanks to this, after the formation of a first crack, fibers effectively provide a through crack stress redistribution which enables new multiple cracks to be formed while controlling the opening of the previously formed ones, which are basically stopped from further widening, up to the unstable localization of one major crack. This makes the material able to "spread" the entity of a single damage (crack) into a series of tightly spaces and narrowly opened multiple cracks, whose single width is hence much less detrimental to the structural durability [10].

The composition of this category of advanced cementitious composites features high contents of cement and supplementary binders, with either pozzolanic (fly ash, silica fume) or delayed cementitious activity (slag) and low water content. The resulting high amount of reactive material which remains un-hydrated and entrapped inside the bulk volume of a structural element may be, upon cracking exposed to outdoor environment, in case featuring presence of liquid or vapor water. These can both activate delayed hydration reactions as well as carbonation ones, whose products precipitate onto the crack surfaces sealing it. The reconstruction of the through crack matrix continuity and, in case, matrix densification at the interface with the fibers, which also yields improved fiber-matrix bond, may also result into "proprie dictum" material healing, i.e. a recovery of the post-cracking mechanical performance, in terms of load bearing capacity, stiffness, toughness and ductility etc [11-13].

Self-healing materials are well known in the field of biology. Blood clotting, skin cicatrization and bone reconstruction are "sparkling" examples of self-healing functionalities inborn in biological materials which material science has successfully attempted to incorporate also in man-made ones, including, among the others, polymers, metals, asphalts, paintings and cement-based construction materials as well [14]. It is blatantly undeniable that the possibility of engineering or stimulating the self-repairing functionalities in cement-based construction materials would enhance the material and structural durability also resulting into reduced maintenance needs over an extended structure service life. In the whole framework herein outlined self-healing cement-based materials would hence represent an exceptional asset for shaping the sustainability of the cement, concrete and construction industry [15].

This paper after, after having outlined the current state of art on self-healing cement-based materials and experimental methods for the assessment of the self-healing capacity, will also critically analyze the current hindrances which challenge the engineering and research community in the "breakthrough in understanding and technology" path which could only lead to a consistent and reliable "design code incorporation" of the self-healing cement-based material concepts.

2. What do we know: autogenous and autonomous (engineered) self-healing

Reportedly known for about two centuries, as from a 1836 "citation" by the French Academy of Sciences with reference to the "cicatrization" of cracks in concrete pipes [16], the self-healing capacity of concrete has been heuristically investigated throughout the last century, studies having literally boomed in the last decade [17,18].

Besides reversible crack closure, due to the swelling of cement paste in the crack flanks, or mechanical clogging, due to debris produced by the same cracking process or by water transported impurities, the main causes of autogenous healing of cement-based materials are the formation of calcium silicate hydrates (C-S-H) due to delayed hydration of binder particles remained anhydrous and suddenly exposed to environment moisture/water upon cracking and/or the precipitation of calcium carbonate ($CaCO_3$) due to the reaction of calcium ions/calcium hydroxide with carbon dioxide either present in the atmosphere or dissolved in water. The first mechanism, which is likely to yield products reconstructing the through crack matrix continuity as strong as the original ones, is likely to prevail in concretes undergoing cracking at earlier ages and/or in concrete containing pozzolanic or latent cementitious additions. The second mechanism, which in terms of effectiveness is likely to prevail over the former though its products are weaker, more frequently happens in old-cracked concrete, the use of supplementary cementitious materials with pozzolanic activity, which favoring, as said above, the former mechanism, counteracts with the latter because of the consumption of calcium hydroxide by the same pozzolanic reactions, which reduces the potential availability of calcium ions [19]. Different techniques have been proposed and validated to stimulate and enhance the aforementioned autogenous healing capacity, making its effectiveness less scattered and more reliable. The most consolidated ones consist in the use of crystalline admixtures [16, 20] and superabsorbent polymers (SAPs) [21].

The latter are characterized by a high water absorption capacity, as high as several times their initial weight. Such a characteristic being reversible, the water initially absorbed by SAPs when added into concrete can constitute a long term reservoir able to feed the self-healing reactions over time. Moreover, if coming into contact with water at a cracked site, the swelling of SAPs can contribute to an initial physical blocking of the cracks, while the chemical healing starts developing. The technique has been validated in [22-26], the obvious negative effects of SAP addition of the concrete strength remaining the major hindrance to its wider use, mainly in load bearing structural applications.

The formers, on their hand, generally consist of a proprietary mix of active chemicals, carried out in a carrier of cement and sand, which, because of their highly hydrophyllic nature, are able to react with water, cement particles but also with the soluble phase of cement hydration products and form CSH and other pore blocking precipitates. These products increase the density of the CSH phase and deposit in the existing capillaries and micro-cracks, activating the self-repairing process. The mechanism is analogous to the formation of CSH and the resulting crystalline deposits become integrally bound with the hydrated cement paste, thus contributing to a significantly increased resistance to water penetration under pressure. Research on crystalline admixtures as stimulators of the autogenous healing capacity has been conducted in [16, 20], confirming the effectiveness of the healing products not only in sealing the cracks, even under aggressive environmental conditions, such as chloride exposure [27] but also in restoring the through-crack stress transfer capacity, both in the case of plain and fiber reinforced concrete [28-30] and under repeated cracking/healing actions [30]. In the case of HPFRCCs an interesting synergy has been highlighted at the fiber-matrix bond level between the dispersed fiber reinforcement and the healing products depositing in the crack, most likely resulting in a sort of distributed "chemical self-prestressing" from which the recovery of the material performance can greatly benefit [31].

The presence of a homogenously dispersed fiber reinforcement, effectively controlling and limiting the crack width, is helpful to self-healing, since narrower cracks are definitely much easier to be healed. Moreover, the technology of fiber reinforced cementitious composites has in the last decade or so pushed ahead the boundary of the "crack propagation control concept" through the developing a signature category of materials broadly known, as above said, as HPFRCCs. The composition of these materials is designed through micromechanics concepts based on the balance between crack tip toughness and fiber pull out work. Once a crack is formed, the crack-sewing and stress redistribution effect provided by the fibers makes it "easier" to form a new crack at another location rather than continuing to open the existing one, which would require to pull out the fibers. The iteration of this concept results into a multiple cracking, with each single crack remaining as narrowly opens as a few tens of microns, and a strain hardening behavior, up until saturation of cracking spacing and unstable localization of one major crack. As a matter of fact, the matrix composition which makes it possible the aforementioned behavior, is characterized by a high content of binders (cement and cement substitutes) and low water content, well below the stoichiometric ratio, which, actually leaving large amounts of un-hydrated and hence potentially reactive binder material, is highly conducive to self-healing. The very narrow width of the cracks guaranteed by the fibers favors a more effective and quicker healing [32-47].

As a matter of fact, the effectiveness of autogenous healing depends not only on the mix composition but on several other interacting factors characterizing the structure service scenario. These parameters range from the environmental conditions, to the age and width of the cracks and also encompass other important, and so far not deeply enough investigated, issues, such as the existence of a sustained through crack stress state and/or repeated actions and their frequency, which may affect the degree and kinetics of healing. The need of guaranteeing not only the effectiveness of the healing mechanism, but also its versatility and repeatability in front of the variety of the structure service scenarios, has led to fruitful development of self-healing engineering techniques, able to provide the required functionality through the incorporation of materials and systems other than the "usual" concrete constituents. These techniques can be grouped into two major categories: encapsulation of polymers and use of bacteria.

In the former, the material which is going to provide the healing functionality in enclosed into capsules which are dispersed into the concrete matrix at the mixing stage. The capsule material and geometry shall be designed so that the capsules do not break during the mixing but do so once they are intercepted by a propagating crack [48-50]. In this respect, it is also of the utmost importance that capsules do homogeneously distribute within the concrete matrix, due to the randomness of crack formation sites. Once capsules intercepted by the crack rupture, the material they contain is released and flows into the crack, and, once hardened, because of its proper polymerization reactions, provides the crack sealing action. A huge variety of materials has been tested, both for the "cargo" and the shell, optimizing in the former case, *e.g.*, the viscosity for a better filling of hairline cracks and, in both cases, the bond with the cementitious matrix, which, in the case of the cargo material is likely to guarantee a stronger and longer persistence of the sealing action and, for the shell, to increase the probability of rupturing upon interception by a propagating crack. Both micro-encapsulation (capsules with a diameter lower than 1 mm) and macro-encapsulation have been investigated, with a large variety of capsule shapes ranging from spherical to tubular [51]. An evolution of the concept is represented by vascular systems [52,53], implementing a biomimetic approach to self-healing, which, besides the evident topological advantage, would also benefit from the further possibility of a supply of the healing material which could be continuous and in case tailored to the nature and amount of the damage to be repaired.

The bacterial approach to self-healing [54-49], on its hand, relies upon the production of calcium carbonate from the microbiological activity of bacteria and other different types of microorganisms, all featuring the ability to survive into the highly alkaline environment of a cementitious matrix, though contributing to the precipitation of calcium carbonates through different metabolic pathways, including:

- Ureolytic bacteria, which though urease produce, from urea and water, ammonia and carbonate ions, which then form calcium carbonate with the calcium available from the matrix; the bacterial activity requires oxygen to be initiated, which may not be easily available deep inside the cracks;
- Denitrifying bacteria, mutuated from solid consolidation techniques, which produce carbonate and bi-carbonate ions from a nutrient source in the form of calcium formates and nitrates;
- Aerobic heterotrophic bacteria, which produce calcium carbonate as a result of aerobic metabolic conversion of organic compounds, such as calcium lactate.

Protection of micro-organisms from the quite harsh cementitious matrix environment and up to the tome of cracking, when their activity will be requested, has been so far successfully attempted through micro-encapsulation, encapsulation in hydrogels and impregnation in porous granules, including lightweight aggregates already commonly employed in (light-weight) concrete technology [60,61].

3. What do we know: experimental characterization of self-healing

Quantifying the effectiveness of a healing technique, be it based either on stimulated autogenous mechanisms or on an engineered process, is a quite comprehensive experimental task which has to encompass a multifold set of variables, ranging from the creation of a “controlled” crack to the implementation of curing conditions representative of the intended service scenarios, as described in the previous section, to the evaluation of the sealing of the crack and/or of the recovery of the engineering property of interest, either mechanical or durability related or both, to the comprehension of the mechanisms underlying the aforementioned macroscopic observation, through characterization of the healing products. Such a thorough assessment is not only needed for the validation of any proposed self-healing technology but has also to constitute the logical framework for the development of self-healing testing standards, which stands as the first step towards the incorporation of self-healing concepts into code-wise durability based design approaches.

A critical review of the testing methodologies for the assessment of self-healing capacity of cement-based materials has been recently provided in [62]. The choice of the methodology to produce/induce a crack/damage to be healed depends, on the one hand, on the property whose healing-related recovery has to be measured but, on the other, also on the type of cement-based material under investigation and on its fracture toughness, i.e. on the stability of its post-cracking response.

In the case of plain concrete preferably three-point bending tests have been used, the determinedness of the crack position making the procedure easier to implement in case feedback signal closed loop test control systems are not available. Moreover, the geometry of the specimen and of the produced crack allows tests based on the post-healing recovery of flexural performance as well as of durability based properties such as sorptivity to be consistently performed.

In the case of fiber reinforced concrete and high performance fiber reinforced cementitious composites, the need of reproducing, also at the lab-characterization scale, the signature multiple cracking, has led four-point bending tests to be preferred or even direct tensile tests. Recovery in terms of strength, stiffness, ductility and deformation capacity can thus be directly quantifiable, as of interest also in the sight of the intended applications of this category of materials.

Splitting tensile tests have also been used in the case of fiber reinforced concrete, fibers appropriately improving the stability of the post-cracking response, and because of the suitability of the test specimens to verify healing induced recovery of permeability or chloride penetration resistance.

In the case of weak materials, such as lime mortars, whose self-healing properties can be of high interest in restoration of building heritage, compression tests have been used to induce a damage by loading to a prescribed fraction of the compressive strength and assessing the healing induced recovery of the same strength as well as of physical properties, related to elastic stress wave propagation [63,64].

As from the cited literature survey, healing related recovery of the material performance has been evaluated with reference to both mechanical and durability properties, depending on the application.

Visual observation of crack closure, and in case its quantification by means of image analysis, has often complemented the investigation, also in an attempt to establish a correlation with the measured recovery of durability related and mechanical properties. In this framework it is of the utmost importance to highlight that, since the properties of sound concrete do evolve with age, as a function of the scenario, the healing induced recovery of both durability and mechanical properties has to be made considering not only the "self-comparison" between the performance of the same specimen, as measured immediately after cracking and after scheduled healing, but also considering the evolution of that same property for sound concrete exposed to the same exposure conditions as cracked/healing ones [65].

The complete comprehension of the problems finally requires the characterization of the healing products, as well as of the mechanisms underlying their formation, which has been so far performed by means of conventional microstructure investigation techniques, including Scanning Electron Microscopy (SEM), in case combined with energy dispersive X-ray analysis (EDX) or X-ray diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), Thermogravimetric Analysis (TGA), though other less conventional techniques, such as X-ray Computed Tomography, Nuclear Magnetic Resonance (NRM) and neutron radiography have also been used [62].

4. What do we need? Paving the way towards "design-code" integration of self-healing concepts.

Any innovative construction technology, for a consistent and widespread adoption in the practice, requires its main concept to be "formulated" in a code-wise framework, which also has to rely upon standardization of experimental techniques to identify the material parameters which have to be employed in the design method equations. In spite of the tremendous developments in the concept and validation of healing stimulating/engineering techniques, as summarized in Section 2 of this paper, the "healing assessment" experimental techniques are far from achieving a standard recognition, their critical reappraisal having been only recently attempted. Such review has appropriately allowed to highlight the hindrances which have so far limited the market penetrability of self-healing technologies, at the same time allowing the clearly identify the main topics which still need and deserve intense research work in order to fill the knowledge gap which still prevents not only a widespread market penetration of self-healing materials and concept but also their recognition in testing and product standards as well as in design guidelines and recommendations.

As a first instance, it has to be remarked that, with the exception of autogenous healing and healing stimulating techniques based on the use of supplementary cementitious materials, crystalline admixtures and, in case, superabsorbent polymers, most of the healing engineering techniques have been often tested with reference to cement pastes and mortars. Scaling up to concrete implies issues such as interaction with coarse aggregates, even since the mixing stage, to be taken into account, with reference to the dispersion of the capsules into a medium featuring larger inclusions as well as to the "dilution" effect in the concrete matrix, where the paste or mortar only represent a limited volume fraction.

Besides this issue, which would call for further technological improvement of the capsule shells and encapsulated cargo materials, including bacterial cultures and feeding sources, what is really required to proof the robustness of any self-healing technology and pave the way for its conscious acceptance by the construction industry is the investigation of the healing effectiveness in real structure service scenarios. To this purpose, a surely not exhaustive list of research needs is hereafter provided.

Since cracks in a structure may form at any time, the "rate of survival" of the healing functionality, whether autogenous or autonomous, should be assessed for cracks forming at ages even significantly older than the conventional 28 or 56 days. Very few studies exist on this topic [29, 65]. Ferrara et al. [29] assessed the autogenous healing capacity of HPFRCC pre-cracked at about one year after casting. They interestingly found that the healing functionality still holds, even if at 50% lower effectiveness than for the same material pre-cracked about two months after casting (in the mix half of the required cement dosage – 1200 kg/m^3 – was replaced with an equivalent volume of slag).

In a real structure, a crack undergoes, if any, the healing process while the structure itself sustains the permanent loads and a fraction of the variable loads; this share of the target design service load can be as high as more than 60-70% in reinforced concrete structures and infrastructures. This implies, cracks in concrete being cohesive in nature and also considering that generally reinforcing bars or dispersed fiber reinforcement cross the cracks, that the same cracks heal under a sustained through-crack stress, whose influence on the kinetics and effectiveness of the healing as well as on the same nature of the healing products has to be suitably investigated. It is furthermore worth remarking that, while in most cases such stresses are tensile, whose effects on the healing may be expected to be detrimental [66, 67], few interestingly representative cases also hold in which, e.g., an early formed crack may experience in the structure service condition a through crack compressive stress state, which may be expected to benefit its healing. This may be the case, for example, of precast tunnel segments, which may experience restrained shrinkage and/or even flexural cracks during transient situations, including transportation and handling, whereas, once the annulus is completed, experience circumferential compressive stresses whose effect is likely to favor the healing [68]. The same may happen with reference to, e.g., restrained shrinkage cracks in pavements (joints) which, because of fixed or moving loads may experience bending moments whose sign is likely to result into through crack compressive stresses.

This also implies the need to include in the healing assessment scenarios moving/repeated loadings, the magnitude and frequency of the likely alternate stresses they can induce onto the crack faces surely affecting, to an extent so far hardly investigated by anyone, the healing mechanisms and kinetics.

In a similar framework the effect of the load rate application is also worth being considered, the effectiveness in the release of the healing agent from capsules of vascular systems being most likely affected by it, which would result, e.g. in case of high strain rates, in a likewise affected effectiveness of the related healing functionality. It is also worth remarking that, even in the case of load events whose frequency may be very low and hence resembling the quasi static loads so far normally investigated in laboratories and in a few pilot real scale studies, the issue of healing/cracking repeatability has to be investigated, also with reference to the rate of “survival” of the healing functionality across the same cracked sites, upon repeated cracking and healing events. Moreover, the possibility as to be evaluated of “engineering” such a good healing, and material stress redistribution capacity, that, upon a repeated loading event the pristinely formed and finally healed crack is so strong that it does not reopen but a new crack is formed elsewhere, through which the same level of healing should be guaranteed [31, 69].

The assessment of the healing capacity in real structure scenarios is quite a challenging task, involving non-conventional experimental capabilities and most of all requiring the investigation to span along a time frame whose extension could hardly match with the needs of an effective and market oriented technology transfer (healing periods up to a few years have been considered in research so far). In this respect the availability of sound and reliable predictive modelling tools becomes of the utmost importance, since only they would allow to extrapolate the results of performed experimental characterization of self-healing capacity of cement-based materials to real structure service scenarios. A review of the currently existing modelling approaches for self-healing of cement-based materials has been recently provided by Jefferson et al. [70], highlighting on the one hand the complex multifold set of phenomena whose appropriate comprehension and description is required. These range from coupled chemical hydration and mechanical behavior and transport properties to simulation of embedded microcapsules, capsule breakage to release and flow of healing agents. On the other hand, such a review has also pointed out the out the paucity of experimental data suitable for proper validation of numerical models and the scattering not only among the values of the experimentally identified material parameters but also among the concept which has informed the experimental investigation, the way in which the parameters have been identified and the same nature of the thus garnered material properties.

This first of all highlights the compelling need, already remarked in the previous section, of standardizing not only the testing methods for the measurement of concrete self-healing capacity, but, hopefully, of achieving a consensus about the philosophy underlying the testing approaches aimed at identifying material parameters which also have to serve as the basis for a design oriented modelling. In this respect, aiming at the formulation of design concepts/approaches incorporating self-healing in a semi-probabilistic format, it has to be clearly kept in mind that the “statistical” processing of experimental data, and their modelling through physical based models, is a fundamental and necessary but surely not sufficient step. The randomness of structure service scenarios, e.g. in terms of environmental conditions, load patterns etc., requires a likewise mathematically sound treatment, playing a role of equal importance in the design concept formulation.

The goal towards which such a “design oriented” predictive modelling activity has to aim, should be, in the author’s opinion, the formulation of a “healable crack width concept”, which would replace the current crack width limits in serviceability limit state design. The healable crack width threshold value, which would form the core of a durability based design approach, calibrated on the basis of the randomness of scenarios and materials, would actually represent the crack width limits that the material would be able to heal, with a given assigned/accepted probability, under the intended environmental conditions and under an assigned and accepted probability that the anticipated cracks will form under the anticipated load combinations and over the intended target design service life.

In order the benefits of self-healing materials to be fully appreciated into an engineering framework but also from the economic point of view, the outcomes of the whole aforementioned activity should be framed into a life cycle analysis approach which together with life cycle cost and social life cycle analysis will quantify the benefits as above in terms of extended material/product/structure service life and reduced maintenance and life cycle cost, including indirect benefits in terms of public awareness of the contribution of the construction industry to the whole sustainability goal.

5. Conclusions

In this paper the topic of self-healing cement-based materials has been dealt with, presenting it also with the aid of state of art reviews recently completed and published in the framework of transnational research collaboration initiative, in the challenging socio-economic context of the construction sector worldwide. Besides reviewing the current state of development of healing technologies and healing assessment testing methods, the paper has also highlighted the most challenging research needs which have to be tackled aiming at fostering the market penetration of self-healing cement-based materials, through incorporation of self-healing concepts into durability based and life cycle design approaches.

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