Application of self-healing materials in architecture and construction industry: an exploratory review

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Abstract- This work's aim was to perform a review of the scientific literature from the standpoint of both the architect and builder. In the first place, on which self-healing materials are currently available for construction industry; secondly, to acknowledge the main applications and the self-healing methods of each material. The review was largely carried out using the scientific database tool *sciencedirect*® and other similar tools on the main applications of self-healing materials in construction industry. The results reveal that the main applications refer to the production of self-healing concretes and mortars by means of self-healing techniques, for example: insertion of microcapsules with various self-healing agents, followed by self-healing bacteria. It is concluded that with the use of these materials not only does the service life of structures of buildings improves, but also that of the entire building, increasing durability and noticeably decreasing maintenance and reparation costs.

Keywords– Smart materials, Self-healing, Construction materials.

I. INTRODUCTION

Construction industry is one with the heaviest impacts on the environment [1, 2, 3]; an instance of this, concrete is the construction material most used in the world [4]. To produce concrete, Portland cement and water are the main ingredients used as agglutinant or bond matrix to join the petrous aggregates (sand + gravel) in a hydration process that concludes with the curing and hardening of concrete within a given time frame.

In the construction of buildings as well as rural and urban infrastructure, a number of the construction materials used can be basically classified in the following categories or families [5]:

- Metals
- Polymers
- Ceramics
- Composites
- Natural materials

All these construction materials are exposed to various degradation factors, adding to possible errors and failures over design, construction, use and maintenance, which brings about defects that because of the proper nature of the materials tend to deteriorate.

For example, in concrete there are cracks and micro-cracks that cause degradation problems inside and on the surface of the material [6]. By and large, cracks in concrete can be defined as something common and acceptable; problems appear when the excessive depth and width as well as a large number of cracks produce structural failures [7]. A typical example of concrete degradation is when a crack exceeds in dimensions and causes the entrance of degradation materials from the outside that can produce corrosion inside the metal both in concrete, which works in compression, and steel, which does in tension.

In like manner, other sorts of materials such as metals, polymers, plastics, ceramics and various composites are exposed to deterioration agents by material defects.

To prevent the degradation and deterioration of materials and extend their service life, preventive and corrective maintenance is basic, as well as numerous methods and strategies to protect the materials such as:

- Reduction of corrosion by means of anticorrosive coatings
- Cathodic protection of reinforcing steel in reinforced concrete
- Concrete coating in reinforcing steel
- Incorporation of fibers and particles embedded in composite materials (ceramic, polymeric or metallic matrix) as reinforcement against internal and external aspects of the material
- Improvement of mixtures regarding the use of cement / water ratio
- Architectural and constructive protection of the construction components against moisture, radiation, carbonation and condensation agents, fungi, dust, etc.
- Use of hydrophobic coatings on the materials' surface
- High-durability finishes in construction components
- Et cetera

At present, there is an innovative technique that directly protects the material from the degradation agents, which refers to the materials' self-healing from the inside, which is the ability or capacity that a material has to repair damages from external and internal agents automatically and autonomously [7]. Self-healing may take two forms:

1. Autonomous self-healing (with no external intervention),
2. Non-autonomous (it requires human help or intervention or of any external agent).

There are various processes for a material to heal itself. The main is self-healing of cracks (as it is the typical case of concrete) which close and protect the material; however, there is also other very similar process, which consists in filling the gaps or holes the material may have and thus increase the performance of mechanical strengths and even the aesthetical appearance of the material.

In order to accomplish this, several strategies of material design are required, since materials for construction industry, and in general, are diverse in nature and with different properties: polymers/plastics, paints/coatings, ceramics/concretes, metallic/steel, etc., which have their own self-healing mechanisms [8].

To design self-healing materials, there are some techniques and methods that largely have to do with chemistry and materials science [8]:

- Releaser of the repairing agent, which is the most used mainly in concrete, a frequently used technique is the insertion of capsules or particles that release self-healing agents inside the material.
- Reversible cross bonds or "reticulation", which is an irreversible process of polymeric materials, it is performed in order to attain higher mechanical strengths such as a high Young's modulus, resistance to solvents and high resistance to fracture.
- Electro-hydro-dynamical, in this technique blood's coagulation process was imitated by means of aggregating colloidal particles in the defective site.
- Conductivity. Polymeric materials are insulating. By providing polymeric systems with conductivity, these materials may become suitable for electronic applications. Adjustable conductivities in polymeric materials may offer information on the structural integrity by means of the electronic feedback that might offer a better idea of the most difficult task of detecting and quantify micro-cracks.
- Shape-memory effect. Certain heavily ordered inter-metallic systems show the known shape memory effect, in which the plastic deformation applied in martensite phase at low temperature may be almost completely inverted in the transformation into austenite phase at high temperature [9, 10].
- Nano-particle migration. Nanoparticles in a polymeric fluid may be segregated in cracks due to the fatigue attraction induced by the polymer between the particles and surface [11].
- Co-deposition. Electrolytic co-deposition can also be used to design self-healing anticorrosive coatings. The microcapsules that contain corrosion inhibitors may be added to composite coatings by means of this method [12].

The main applications of self-healing materials nowadays in construction industry summarize as follows:

- Self-healing concrete and mortars
- Self-healing metallic structures
- Self-healing waterproof coatings

- Self-healing paints
- Self-healing polyurethane
- Self-healing thermosetting polymers
- Compounds reinforced with self-healing fibers

The goal of this work is to carry out a review of the scientific literature from the standpoint of the architect and builder, firstly on which self-healing materials are available for construction industry and secondly find out the main applications and self-healing methods of each material.

The use of techniques and strategies for self-healing materials in construction industry is fully justified as any material may produce micro-cracks and other defects which propitiate structural damage in construction systems, and on so, it produces excessive expenditures in preventive and corrective maintenance as well as costly repairs. In like manner, it is justified to resort to these novel techniques to help prolong the service life of buildings and their durability. Service life understood as the time after installation or construction over which a building or its parts meet or exceed the requirements they were designed and built for [13]. Durability understood as the capacity of a building or component to reach the optimal performance of its functions within a certain environment or place, for certain time with no significant corrective maintenance or repairs [14].

Self-heling properties in materials are still under research and at early stages of commercialization and product application, however in the near future they will be a reality at economically acceptable prices, which help their use and implementation in various industries, including construction.

As the industry more openly accepts these innovative self-healing techniques, their everyday use will increase. At present, self-healing materials are a technical reality and the fact there is so much interest in the research and scientific development of these innovative technologies is because it has a high potential of technical and economic feasibility as well as social and environmental, as it is a technological innovation that might save numerous natural and economic resources in the future from the construction of infrastructure, buildings and cities

II. METHODOLOGY

A review of exploratory nature of the literature was carried out by means of a main category: a review of the scientific literature on the applications in construction industry of self-healing materials.

The review was mainly carried out with the help of the *sciencedirect*® database tool, and other similar, on the main applications of self-healing materials in construction industry, gathering information in the following format (table 1).

Table 1. Format to gather the information from the scientific literature on self-healing materials in construction industry

Bibliographic reference	Work’s main aim

Source: Author's own elaboration.

Later on, in order to process the information, the following data were analyzed:

- Material in question, determined by type and nature
- Main uses and applications in construction industry
- Identified self-healing technique

Finally, the format below was used for presenting the results (table 2):

Table 2. Format to interpret the review of the scientific literature referring to the applications of self-healing materials in construction industry

Bibliographic reference	Self-healing material	Main applications	Self-healing technique

Source: Author's own elaboration.

III. RESULTS

The results of the review of the scientific literature related to applications of self-healing materials in construction industry are shown in:

- Table 3, the aim of the revised work is emphasized
- Table 4, the material in question, its applications and its identified self-repairing technique are emphasized

Table 3. Review of the scientific literature on the application of self-healing materials in construction industry: description and works' objective

Bibliographic reference	Works' main aim
[15]	This work reports a simple versatile strategy to build self-healing hydrogels with adjustable mechanical properties and shape-memory behavior
[16]	This work explores the possibility of using Ti particles incrusted in microns to heal surface cracks in alumina and disentangle the evolution of the crack-filling process in case of oxidation in pure solid state.
[17]	Self-healing biomimetic super-amphiphobicity on a rough alumina surface with a large amount of nano-pores that act as nano-consumption as low surface energy materials that can release and consecutively heal the damaged surface is reported.
[18]	This article presents the synthesis of two different calcium alginate polymeric fibers that encapsulate the rejuvenator by means of a microfluidic device: i) hollow streams of rejuvenation of encapsulation of hollow polymeric calcium alginate fibers; ii) polymeric fibers of compartmented calcium alginate that encapsulate drops of rejuvenator.
[19]	In this research capsules of calcium alginate, which contains sunflower oil at various water/oil proportions, were synthesized and their physical properties, morphologic characteristics, thermodynamic performance, oil content and survival capacity were studied after mixing, compacting and selecting the most suitable for an asphalt mix.
[20]	In this article the flow behavior and self-healing properties of asphalt agglutinants with various aging degrees were researched.
[21]	The goal of this research is to prepare the microcapsule and study the rheological and self-healing properties of the microcapsules that contain asphalt.
[22]	This study offers a quantitative assessment of the self-healing of thermal-induced damage in asphalt concrete by means of acoustic emission (AE) as well as disc-shaped compact tension tests.
[23]	In this research a new encapsulating rejuvenator of self-healing Ca/silicon alginate fiber compartmented by micro-fluidic methods was synthesized.
[24]	This document revises the applications and latest developments in recent years of a sort of smart devices to store energy.
[25]	This article describes the development of recovered granules as a self-healing system in cement-based materials. Pan pelleting was resorted to produce granules from three different powdered minerals as prospective healing agents: reactive magnesium oxide (MgO), silica fume and bentonite.
[26]	This study proposes for the first time the production of microcapsules with characteristics customized for the mechanically-activated self-healing action based on cement.
[27]	In this study the St-DVB microcapsules that contain epoxy resins as adhesive agent were incrusted into cement paste in order to achieve self-healing capacity.
[28]	Self-healing microcapsules were synthesized by in situ polymerization with a melamine urea-formaldehyde resin shell and an epoxy resin adhesive.

[29]	This article is the second part of a complementary study focused on the autogenous self-healing capacity of cement composites reinforced with high performance fiber (HPFRCC).
[30]	Strain hardening cement composites (SHCC) exhibit a number of characteristics of cracks when they bear a load in flexion or traction. In this document, SHCC samples were preloaded under a three-point flexion to introduce multiple micro-fissures and were exposed to different conditions to assess their self-healing.
[31]	Research on the self-healing capacity of engineering cement composites (ECC) with excellent tension deformation capacity and multiple cracking capacity is a candent topic. In the document, both destructive and non-destructive methods are resorted to in order to track the self-healing process of ECC in wet-dry cycles, which are ultrasonic measurement, absorption test and direct traction test, respectively.
[32]	This research focuses on the effect of replacing the limestone powder with cement material in engineering cement composite performance that contains high-volume fly ash.
[33]	The effect of dosages of the expansive MgO-type agent and fly ashes of various types as replacements for cement was researched on the basis of the lowest expansion characteristics of the bars. Cement composite designed –MgO by means of linear expansion tests both in water and “auto-clave”.
[34]	For this research, recovered expanded perlite was used for immobilizing the bacterial spores and encapsulating nutrients such as two separate components for self-healing concrete. Self-healing capacity was assessed by means of images and the initial absorption of water by the surface.
[35]	The effects of heat, depletion of nutrients and pH treatments were examined; all of them designed to mimic the conditions of fresh cement paste on ureolithic bacterium *Sporosarcina pasteurii*; specifically, the impacts on bacterial viability, the capacity to hydrolyze urea and the surface load were assessed.
[36]	The article researches the effect of capsules on damage resistance by considering constitutive models of fractures. The fracture resistance of the samples with capsules increases up to 35% in comparison with the reference.
[37]	Self-healing under multiple damage cycles is critical for the concrete structures’ service capacity. This article explores the mechanical and permeability properties of multiple (i.e., three) damage cycles comparing autogenous self-healing and PVA, super absorbent polymer and bacteria immobilized in biochar.
[38]	Microbial calcium carbonate offers an attractive biotechnology to fill the pores’ volume, as well as micro and macro cracks in the affected cement material, which becomes barriers to hinder water or the aggressive chemical fluid. The present study describes a theoretical model to simulate the kinetics of induced calcite precipitation as a response for the hydrolysis of urea in concrete cracks.
[39]	This document focuses on a self-healing technique called microcapsules, which contain a healing agent that is released as a result of crack propagation. The document presents details on the microcapsules, their implementation in both concrete and field tests as well as assessment in laboratory.
[40]	Microcapsules with Toluene di-isocyanate (TDI) as a nucleus and paraffin as shell for concrete’s self-healing they were prepared using the condensation method in melt state and the effects of preparation temperature, stirring speed, and the mass ratio of paraffin / TDI in the central fraction of studied microcapsules.
[41]	This study presents the development of a new active control technique of the crack width to significantly reduce the variation of crack width in a series of cracks, which becomes more

	consistent permeability results.
[42]	A novel self-healing chemical system with microcapsules of Sodium mono-fluorophosphate/ethyl cellulose is designed with a view to inhibiting corrosion in reinforcing steel in concrete materials under NaCl solution.
[43]	This work researched self-healing coatings for reinforcing steel to introduce an autonomous healing system for damaged coatings.
[44]	In this study self-healing solid capsules were produced using cement powder for the self-healing of cracks of concrete structure.
[45]	The present study was designed and implemented to explore not only the effects of urease bacteria as a self-healing agent incorporated into a mix of mortar, but also the various curing environments on the mortar’s durability.
[46]	This novel graphene-epoxy nanocomposite has self-healing efficacious and superior anti-penetration functions, at once providing the coatings with smart anticorrosive performance.
[47]	This article presents a thorough study of the self-healing properties of various polymer nanocomposites that use a series of curing mechanisms, including the addition of various healing agents.
[48]	They designed and synthetized a self-healing material based on polymer / graphene with a structure of reticulation net by means of the Diels-Alder reaction.
[49]	In this document, a sort of thermoplastic polyurethane which contains Diels-Alder bonds has been successfully synthesized.
[50]	In this document, three sorts of concrete beams with two different lengths of adhesive of encapsulated polyurethane were tested and the self-healing performance was measured applying a static torsion load.

Source: author’s own elaboration based on the review of the scientific literature recorded in the first column of this table.

In table 3, the review of the scientific literature on the applications of self-healing materials in construction industry, detailing the goal of the work. It was found that some studies focus on producing and characterizing self-healing materials, while other studies only refer to the assessment and analysis of some self-healing materials.

Table 4. Interpretation of the review of the scientific literature referring to the applications of self-healing materials in construction industry, including self-healing techniques

Bibliographic reference	Self-healing material	Main applications	Self-healing technique
[15]	Poly-acrylic acid	Hydrogels with shape-memory behavior for surfaces and hydrophobic finishes	Induced by multi-amines
[16]	Alumina	Self-healing aluminum	Incrusted titanium micro-particles
[17]	Alumina	Self-healing aluminum	Using low surface energy materials
[18]	Asphalt	Pavements and other surfaces	Micro-fluidic synthesis of polymeric particles

[19]	Asphalt	Pavements and other surfaces	Synthesis and characterization of multiple-cavity calcium alginate
[20]	Asphalt	Pavements and other surfaces	Not applicable
[21]	Asphalt	Pavements and other surfaces	Not applicable
[22]	Asphalt	Pavements and other surfaces	Not applicable
[23]	Asphalt	Pavements and other surfaces	Micro-fluidic synthesis of polymeric fibers
[24]	Lithium, Gallium, Titanium	Batteries and supercapacitors	Lithiation and dimerization
[25]	Cements	Cement-based composites (concretes and mortars)	Polymeric preparation and encapsulation of mineral powder granules
[26]	Cements	Cement-based composites (concretes and mortars)	Micro-fluidic production of custom microcapsules
[27]	Cements	Cement-based composites (concretes and mortars)	Microcapsules that contain epoxy resins as adhesive agents were incrusted in cement to accomplish self-healing capacity
[28]	Cements	Cement-based composites (concretes and mortars)	By means of inserting microcapsules of Urea-formaldehyde melamine
[29]	Cements	Cement-based composites (concretes and mortars)	Not applicable
[30]	Cements	Cement-based composites (concretes and mortars)	Not applicable
[31]	Cements	Cement-based composites (concretes and mortars)	Not applicable
[32]	Cements	Cement-based composites (concretes and mortars)	Design and production of limestone powder as bound matrix.
[33]	Cements	Cement-based composites (concretes and mortars)	Design and production of mixtures with large volumes of fly ash and expansive agent of magnesium oxide (MgO) type
[34]	Concrete	Structures for buildings	Application of encapsulated bacteria of expanded perlite
[35]	Concrete	Structures for buildings	Bio-mineralizing bacteria
[36]	Concrete	Structures for buildings	Not applicable
[37]	Concrete	Structures for buildings	Bacteria immobilized with biochar

			and superabsorbent polymers
[38]	Concrete	Structures for buildings	Insertion of microbial calcium carbonate
[39]	Concrete	Structures for buildings	Microcapsule insertion
[40]	Concrete	Structures for buildings	Insertion of microcapsules that contain Toluene diisocyanate
[41]	Concrete	Structures for buildings	Not applicable
[42]	Concrete	Structures for buildings	Use of Mono-fluorophosphate / ethyl cellulose microcapsules
[43]	Epoxy	Epoxy coating for reinforcing steel	Use of microcapsules as reparable agent
[44]	Mortar and cements	Production of concretes and mortars	Use of self-healing solid capsule
[45]	Mortar and cements	Production of concretes and mortars	Use of urease bacterium embedded in mortar
[46]	Nanocomposite of graphene epoxy	Anticorrosion coatings	Synthesis of graphene-cyclodextrin-epoxy
[47]	Polymer nanocomposite	Anticorrosion coatings	Addition of various repairing agents
[48]	Polymer/graphene	Anticorrosion coatings	Diels-Alder reaction
[49]	Polyurethane	Insulating materials for construction, coatings and adhesives	Diels-Alder reaction
[50]	Polyurethane	Insulating materials for construction, coatings and adhesives	Not applicable
NB: 'Not applicable' refers to the fact that the study only focused on assessing the self-healing material, not on producing it.			

Source: author's own elaboration on the basis of the review of the scientific literature registered in the first column of this table.

Table 4 presents the review of the scientific literature regarding the applications of self-healing materials in construction industry, including the source (column 1, table 4), the self-healing material, object of study (column 2, table 4); applications in construction industry (column 3, table 4) and the self-healing techniques. There were some studies that referred to assessment or analyses of some materials in which it was not applicable to mention the material's self-healing technique. For example, [50] study a polyurethane case in which the objective was to test three sorts of concrete beams with two different encapsulated polyurethane adhesive lengths and the performance of self-healing was measured applying a static tension load, so the goal focused on measuring the mechanical strengths of materials produced as test specimens. It may be said that these specimens were produced with self-healing techniques, in this case of insertion of self-healing agent capsules, though not as the study's main goal.

On the contrary, [51] mention that in order to produce self-healing asphalt, a technique of synthesis and characterization of multiple-cavity calcium alginate capsules can be carried out; it consists in inserting capsules of calcium alginate in various and diverse sizes and shapes into the asphalt mix over its preparation, which will propitiate to fill the holes or cracks which over time appear inside the material.

IV. CONCLUSIONS

When a review of the scientific literature on applications and study cases of any topic is performed, it may be, as in the case here, there were two sorts of reviewed studies: the first and largely referring to the way how self-healing materials can be produced for various and diverse applications, while the second sort may be studies that only focus on assessing certain self-healing materials. Both are useful, but it is concluded that we first have to acknowledge the techniques to produce self-healing materials to later perform better assessments and analyses of such materials so as to apply them in a better manner in industry.

The studies most frequently carried out are:

1. Self-healing concretes and mortars
2. Self-healing cement composites
3. Self-healing asphalts
4. Self-healing polymers
5. Self-healing metals

In this way, it can be concluded that the most important self-healing materials in construction industry are cement-based concretes mainly with applications for buildings' structures. With this application not only the structures' service life increases, but also that of entire buildings, increasing their durability and noticeably decreasing maintenance and reparation costs.

Out of the sources reviewed in the sample of the present study, the country that prevails in research on self-healing materials is the country of China, followed by the United States, United Kingdom, Canada, Belgium, South Korea, Iran, the Netherlands, Italy, Singapore and Malaysia. However, the above is only a sample but which verifies by far that China is having a great boom in many fields of knowledge and for many countries it is a clear example to follow.

The most resorted technique is micro-capsule insertion with various self-healing agents, followed by the use of bacteria, Diels-Alder reaction, polymeric fibers synthesis, insertion of titanium microcapsules, multi-amine, lime powder and microbial calcium carbonates.

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