JOURNAL OF MATERIALS & CONSTRUCTION

Journal of Materials and Construction
ISSN 2734-9438
Website: www. jomc.vn

A review on current direct and indirect testing methods as high-effective techniques in the evaluation of self-healing ability in concrete

Nguyen Ngoc Tri Huynh[1], Tran Anh Tu[1], Nguyen Khanh Son[1], Kei-ichi Imamoto[2], Chizuru Kiyohara[2]

[1] Faculty of Materials Technology, Ho Chi Minh City University of Technology, VNU-HCM, 268 Ly Thuong Kiet St., Ward 14, District 10, HCM City, Vietnam

[2] Department of Architecture, Tokyo University of Science, 6-3-1, Niijuku, Katsushika-ku, Tokyo, Japan

KEYWORDS

Self-healing concrete
MICP
Capsule
Controlled-release

ABSTRACT

As it has been using more than 100 years, concrete is a high compressive strength construction material and relatively easy to maintain and manage for buildings and infrastructures. However, with the increasing technical requirements of society for new constructions, various technologies have been developed to improve the strength, performance, and durability of concrete and overcome weaknesses, including the cracking phenomenon. The crack handling of concrete structures is a research hotspot and has caused long-term problems for the development of the engineering community. Currently, research on the world's self-healing concrete technology has been conducted in various ways. Also, promising progress has been made in different research approaches, but most are still in theoretical feasibility and laboratory-scale. Although there have been many reviews or mini-review papers published, aggregation, refinement, and criticism have never been redundant in light of the continued increase in the number of new publications. This paper has summarized the experimental research methods and results of different types of self-healing concrete in recent years and expounded the mechanism of its action, especially in the trend of using microorganisms for sustainable development. We also point out the outstanding issues and limitations in the studies and propose solutions.

1. Introduction

In 2009, the state-of-the-art report about autogenous healing in cementitious materials was published, and a summary of their findings. In 2012, a special issue of "Journal of Advanced Concrete Technology" in Japan, which summarizes progress in self-healing cementitious materials, was published. Through the studies, three main contents are the quantitative evaluation of self-healing performance, such as water leakage control and loading damage recovery, the investigation into self-healing mechanism, and application of the non-destructive tests to identify self-healing results. Every year, with the rapid increase in the number of publications globally, research teams in Japan have worked on many projects involving self-healing techniques in concrete. Also, the Japanese industry has a high interest in self-healing materials, especially concrete. In 2019, as the first time a conference of "Self-Healing Materials Community" was held in an Asian country, "The 7th International Conference on Self-healing Materials (ICSHM2019)" in Yokohama-Japan gathered many audiences such as international researchers, lecturers, and engineers.

For many cases, an array of definitions in the self-healing topic may make confused. Return to the origin, "Japan Concrete Institute" (JCI) [1], [2] defined (Figure 1) (X) "Autogenous healing" as "a natural process of filling and sealing cracks without any external operations and works"; (Y) "Engineered Healing/Repairing" as artificial and intentional methods for filling and sealing cracks"; (**X**∪**Y**) "Self-healing/Repairing" as "processes of filling and sealing cracks that automatically take place in situ without any practical works by workers"; (A) "Natural healing" as "natural phenomena of filling and sealing cracks that result from some chemical reactions (late hydration and carbonation) or mechanical blocking at crack faces"; (B) "Autonomic healing" as "involuntary healing of cracks that are provided by admixtures"; (C) "Activated repairing" as "automatic repairing using some artificial devices which usually consist of sensors and actuators"; and (**X**∪**Y**) "Engineered healing/Repairing" as general repairing which needs practical works and treatments in situ by workers". Furthermore, by "Reunion Internationale des Laboratoires et Experts des Materiaux" (RILEM), self-healing can be defined as "any process by the material itself involving the recovery and hence improvement of a performance after an earlier action that had reduced the performance of the material". RILEM also defined that "Autogenic" as "the self-healing process is autogenic when the recovery process uses materials components that could otherwise also be present when not specifically designed for self-healing (own generic materials)"; and "Autonomic" as the self-healing process is autonomic when the recovery process uses materials components that would otherwise not be found in the material (engineered additions)".For many cases, an array

Corresponding author: nnthuynh@hcmut.edu.vn
Received 17/10/2021, Revised 04/11/2021, Accepted 21/04/2022
Link DOI: https://doi.org/10.54772/jomc.v12i01.326

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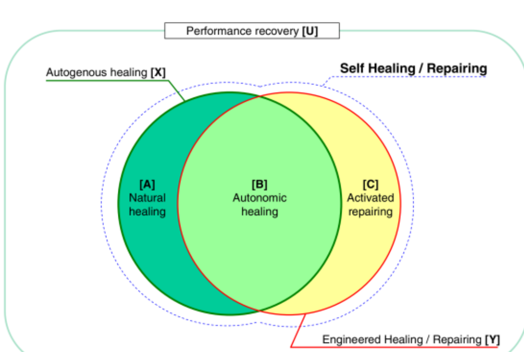
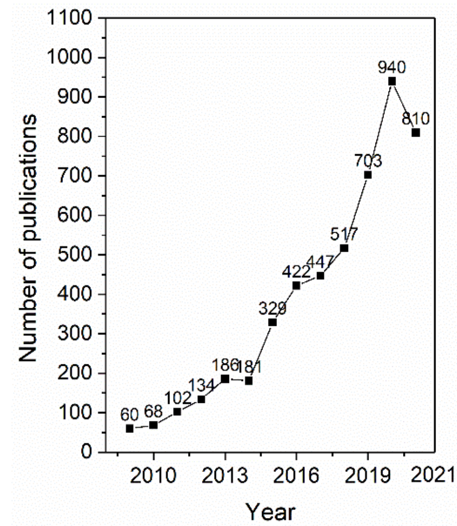
It can be seen that autogenous healing is a common phenomenon in a human/animal or any living body. However, the beneficial effects of this well-known phenomenon and its limitations in application fields have not been well understood yet. There are many approaches to self-healing in concrete with several research groups based on their essential healing mechanisms. Experimental results confirmed that crack size up to 0.1 mm could be healed by autogenous self-healing mechanism, while crack size up to 1mm can be healed by autonomous self-healing mechanism. It has been observed that the therapeutic effect entirely depends on the specific exposure to the respective environment, the type of healing agent used, and techniques followed.



(a)



(b)

Figure 1. Venn diagram of self-healing terminology according to JCI TC-075B (a). Number of publications in the world per year in the topic of "self-healing concrete". Source: "Google Sholar" database (b).

2. Types of self-healing concrete

Different types of self-healing concrete can include: (i) natural self-healing based on concrete itself, (ii) self-healing based on using permeable crystal, (iii) self-healing based on shape memory alloy or polymer, (iv) self-healing based on bionic self-repair, (v) self-healing based on microbial induced calcium carbonate. This paper focuses on one of the most extractive trends, self-healing using microorganisms (bacteria, fungus, yeast) with its biomineralization ability. Also, the natural self-healing phenomenon was mentioned with support processes for the total effect of self-healing. The continuous hydration of the remaining cement particles contributes relatively partially to the total level of self-recovery and the strength and durability of concrete. However, it should be clarified that relying only on this natural healing effect is not sufficient to maintain and protect buildings for long periods of use under the influence of external forces and environmental impacts. Moreover, in the case of low humidity or dry conditions, the hydration process almost cannot occur. Therefore, using highly effective techniques such as engineering self-healing techniques for concrete remains a long-term and sustainable solution. In addition, modern self-cracking/self-repairing techniques are always supported by natural self-healing. When the quantitative and determine the capacity of the self-healing/self-repairing technique is necessary, the separation of these two factors to evaluate each technique is still unclear. Of course, scientists also identified and calculated these factors in their experiments. Also, specific standards are needed in establishing experiments and evaluation methods with high accuracy.

Table 1. Mechanism and characteristics of self-healing based on microbial induced calcium carbonate and natural self-healing.

	Natural self-healing	Self-healing based on microbial induced calcium carbonate
Mechanism	-Moisture and air enter the concrete structure through cracks, promote the unhydrated cement particles to undergo further hydration. -Dissolved Ca^{2+} ions react with solved CO_3^{2-} to form CaO_3 [3].	-Microorganisms are introduced to the concrete mixture or by injection/ spraying to the hardened concrete structure. -The biomineralization forms primary $CaCO_3$ crystals. Then, secondary $CaCO_3$ can be form based on these initial $CaCO_3$ crystallization nucleus or the result of the combination between $Ca(OH)_2$ in the hydrated cement matrix and emission CO_2 from the activities of microorganisms [4], [5].
Benifits	-Precipitated products are condensed and accumulate, eventually blocking the cracks. -In the short-term, less than 0.1mm crack can be healed [3].	Healing products have excellent comparative properties with concrete substrates, such as thermal expansion, similar composition, and the ability to repeat the process of self-healing [6]–[8].
Limits	-Need water/moisture for the late hydration and carbonation reactions. -There is a damage threshold for each concrete type and mixture [9]. If the crack/damage is lower than the damage threshold, the self-healing rate increases with the crack/damage amount. Conversely, if the crack/damage exceeds the damage threshold, the self-healing rate decreases with the crack/damage amount increase.	When adding microorganisms directly to the concrete mixture, their survival ability can be reduced quickly, and their self-healing ability can only be maintained from 1-7 days [10].
Factors affecting	-Mixture proportion, the age of the crack, appears the level of crack/damage, and environmental conditions (thermal, humidity, pH) can significantly affect the healing capacity. -The crack narrow also affects the healing process [11]. The more narrow cracks, the higher the healing capacity.	-The higher the content of the self-healing agent in the mixture, the longer the setting time will increase, but the compressive strength and workability may increase. -The self-healing ability depends on the main factors, including the type of microorganism, the protection for them when placed in concrete, the concentration of Ca^{2+} ions, the concentration of carbon (inorganic), and the environmental factors which can affect the mineralization process (such as pH, temperature)

3. Quantification methods of self-healing ability

3.1. Direct quantification methods

Observation and identifying the self-healing effects in concrete were mentioned and studied by a full array of testings included non-destructive (Ultrasonic Pulse Velocity, Acoustic Emission, water permeability, microscopical) and destructive methods (compressive strength, flexural strength). However, quantification of the self-healing effect has been caused by certain problems for researchers. There is almost no specific standard for this matter [12]. In general, different studies use different assessment methods. Nevertheless, it can be gathered into two main trends: direct evaluation through crack parameters, indirect assessment through mechanical strength, or water permeability. To directly assess (Table 4) the effect of self-healing, many studies performed measurement and calculation of dimensional change (length, width, area) of cracks through the optical microscope, magnifying magnifier, SEM/EDS, or X-ray tomography/CT-scan. These methods are based on image recognition and processing techniques.

Besides visual factors, there are also many limitations when cracks can be omitted or the cracks are not detected. This paper focuses on the most common use techniques, so the microstructural testing methods as X-ray tomography/CT-scan, which can visually determine the crack healing in concrete (3D images), will not be analyzed deeply. Figure 2 depicts some studies using photo-analysis techniques to handle crack images, converting from real photos to binary monochrome images, from which measurement and calculation of parameters are performed.

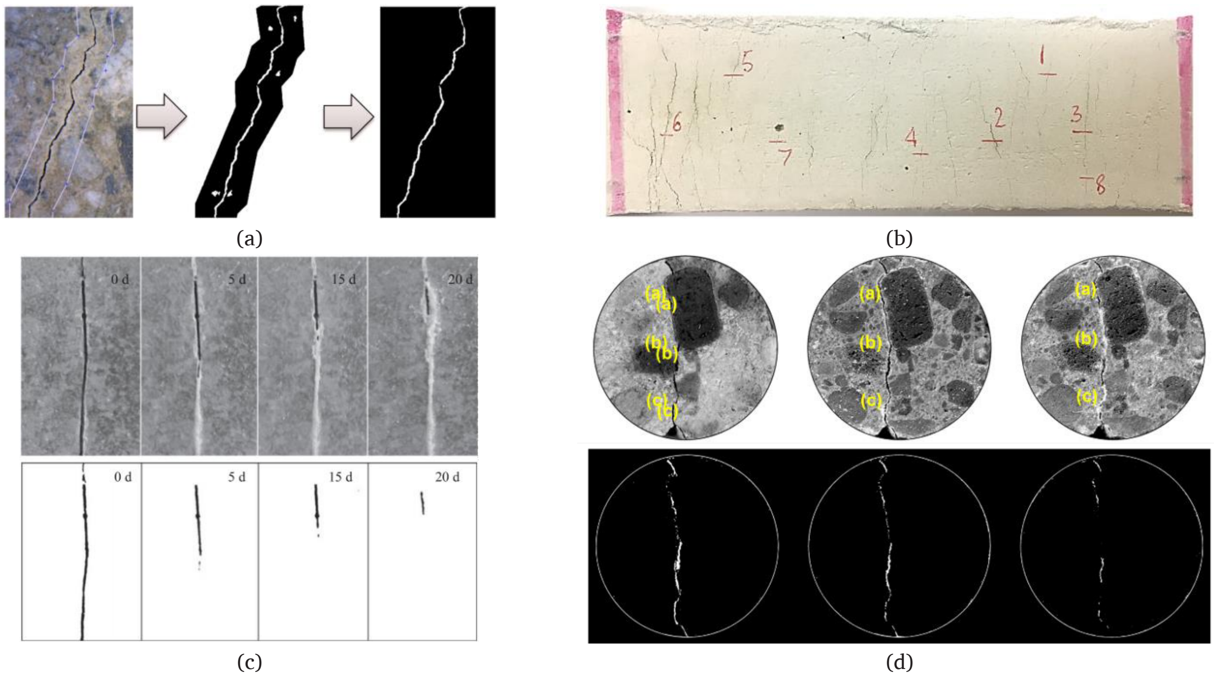


Figure 2. Crack area detection by image processing: crack region definition, image binarization output, and final output (a) [13]. Cracking measurements map within the gauge length (b) [14]. Surface binarization images of specimens with different crack width after different repair time (c) [15], (d) [8].

3.2. Indirect quantification methods

In almost all studies, the self-healing capacity can reach high levels under high moisture conditions or underwater curing, much more effective than the dry curing environment. The compressive strength restoration of concrete specimens cracked at 7-day in advance is significantly higher than those at 28 days or longer. It can be explained that the cracks inside the concrete structure can be repaired and healed during the hydration of cement particles during short-term curing (7 days). Therefore, after a more extended curing period, the long age of cracks, cement hydration perfection is limited. This process can considerably affect the results of the self-healing capacity. Hence, when using the strength restoration test to determine the self-healing capacity, it is necessary to carry out with different age cracks. Additionally, with the combination of the permeability test, it is necessary to compare the crack healing effect at low and high water pressure and a static or continuous flow. In some experimental cases, self-healing products can fill cracks and waterproofing with small and static pressure water flow. However, when the water pressure is high and continuous, the product can immediately be washed away (partially or wholly), affecting the quality of self-healing concrete. Therefore, an effective technique that should be used as a pair with strength testing technique for evaluating healing capacity is testing concrete with ultrasonic pulse velocity. Mechanical resistance, water permeability, and ultrasound properties measurements should be used simultaneously to support each other to create a comprehensive picture of the healing agent's effects in concrete structures.

In the case of the fully cracked concrete specimen, the entire wave is reflected. The crack filled with healing materials has an acoustic impedance lower than the original concrete without crack. Note that the ratio of transmission and reflection from the cracked region in concrete structure is dependent on the relative acoustic impedances of concrete and the healing materials. Also, ultrasonic waveform analysis can be used to evaluate the crack and crack healing in concrete. When the concrete cracked, the maximum amplitudes decreased obviously due to weakened ultrasonic energy by the interference of the air in cracks. Then, if the crack can be healed, the maximum amplitudes increased again.

Another application of ultrasonic technology is to calculate crack depth. The ultrasonic waves will propagate around open cracks rather than directly through cracks, increasing transmission time. If the crack can be healed, the wave can pass through the healing products formed to fill the crack and then reduce the transmission time (still different from the original signal without cracking). Therefore, the depth of the crack can be calculated by measuring the wave propagation time. Moreover, studying the pulse velocity change over curing time can give information about structure changing after the healing process. Besides, the damage degree, the time-dependent self-sealing degree, and the relationship between them can be investigated using the UPV test [30] as the following equation.

Table 2. Indirect quantification methods of self-healing ability.

		Description	Reference
1	Compressive strength	$$H(\%) = \frac{F_c(control) - F_h(healed)}{F_c(control)} \times 100$$ Where: F_c(control): compressive strength of the controlled specimen. F_h(healed): compressive strength of the healed specimen.	[16]
2	Compressive strength restoration	$$H(\%) = \frac{F_t - F_0}{F_0} \times 100$$ Where: F_t: compressive strength of specimens with healing agent after curing time t. F_0: compressive strength of specimens without healing agent after curing time t. The load for cracking is up to 90% of the compressive load at respective days of pre-cracking (3, 7, 14, 28).	[8]
3	Compressive strength restoration	$$H(\%) = 1 - \frac{C_{u_{28}} - C_R}{C_{u_{28}}} \times 100$$ Where: C_{u28}: maximum compressive strength at 28 days. C_R: regained compressive strength after 28 days of curing. The load for cracking is up to 80% of the compressive load at respective days of pre-cracking (3, 7, 28).	[17]
		Recovery rate of compressive strength: $$H(\%) = \frac{F_1}{F_0} \times 100$$ Where: F_0: compressive strength of mortar after curing for i day. F_1: compressive strength of pre-damage mortar after curing for i day	[18]
4	Flexual strength (3-points bending)	$$H = \frac{\sigma_2}{\sigma_1}$$ Where: σ_2: maximum compressive strength of self-healing specimen. σ_1: maximum compressive strength of controlled specimen.	[19]
5	Flexual strength restoration (3-points bending)	$$LRI = \left(\frac{P_r - P_u}{P_p - P_u}\right) \times 100$$ Where: LRI: Load Recovery Index P_r: peak load obtained during the reloading stage. P_p: peak load reached during the pre-loading (for cracks creation) stage. P_u: residual load obtained at the moment of unloading preceding the re-loading stage.	[20]
		$$LRI_n = \left(\frac{P_r - P_u}{P_p - P_u}\right) \times 100$$ n: re-loading cycle index	[15], [21]
6	Water flow/water permeability test	$$H = 1 - \frac{Final\ flow}{Initial\ flow} = 1 - \frac{q_F}{q_0}$$ Where: q_F: water flow at the beginning q_F: water flow after healing	[22]
		$$H = \frac{V_0 - V_t}{V_0} \times 100\%$$ Where: V_0: water permeation velocity of the original specimen (cracked specimen before healing). V_t: water permeation velocity of repaired specimen at time t.	[15], [23], [24]

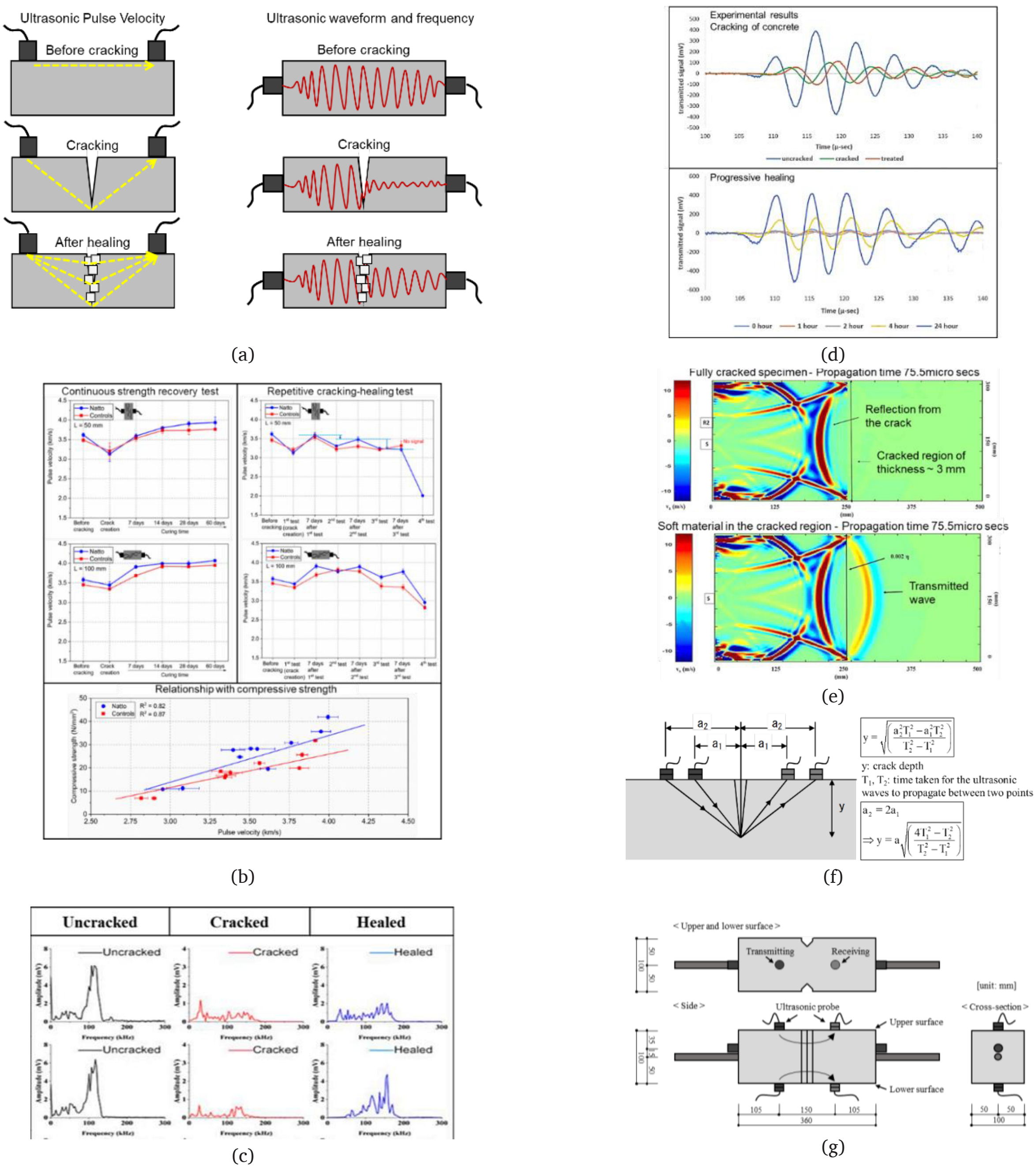


Figure 3. Ultrasonic schematic diagram (a). Evaluate the change in concrete structure by the change of pulse velocity through the different directions of concrete specimens over time and the relationship with compressive strength (b) [8]. Ultrasonic frequency analysis of concrete samples (c) [25]. Experimental results using Reflection analysis (d) and numerical simulation results using wave propagation (e) [26]. The propagation time of the ultrasonic waves on the upper and lower surfaces confirms that the repair agent filled the cracks (f) [27]. Crack depth calculation by measuring the ultrasonic waves propagating time (g) [19], [28], [29].

4. Current challenges and proposed solutions for choosing suitable testing strategies

From many experimental studies, after summarizing the advantages and disadvantages of each trend and approach, it is possible to present some limitations and problems in the field of self-healing concrete as follows.

4.1. Real-scale experiments with large-scale specimens

Although image-analysis is one of the most commonly used methods in evaluating and quantitative the self-healing ability, there are still many disadvantages. For example, with optical microscopic observation, the resolution is very limit. For the SEM, the small space of the specimen chamber is inconvenient. Also, the SEM instrument operates at low pressure, which can dehydrate the concrete specimens and alter the microstructure. Even the most modern tomography technique (CT-scan) using X-ray to create the 3D model can only apply to small specimens. The usability and visualization of the direct evaluation method group are undeniable through the crack parameters. However, this method quickly generates errors from tracking, recording, identifying crack areas, processing images, and calculating results. It is not easy to keep the same observation conditions for a long time with different types of testing specimens from shape to size; the sensitivity, accuracy of the camera, and display image resolution also contribute to the accuracy. Besides, visual evaluation with many testing specimens will lead to a significant increase in data. Since then, it is only possible to care about one or a few specific cracks in each test piece. Therefore, it is necessary to evaluate concrete specimens through physical-mechanical behaviors to get closer to the actual conditions that cracks appear much unevenly and may not be directly observed. Methods for assessing self-efficacy are not consistent. For example, level/speed/rate of self-healing, self-healing for multi-cracks at different positions, mechanical strength after self-healing. With a series of standardization of empirical methods and performance evaluation, experimental studies will be able to move to a large-scale and become closer to real-scale quickly.

Most research results only show the effectiveness of the self-healing process for small and single cracks. Although the initial goal of engineering self-healing is to treat early cracks on a micro-scale and prevent them from developing into larger cracks; many experimental results show the ability of these techniques to respond to cracks in long age with significant effectiveness. Therefore, a full array of studies on the effective-healing crack range with specific treatment guidelines should be considered. Besides, some properties of concrete after self-healing have not been investigated and clarified, such as changes in mechanical strength, elastic modulus, and material properties. Evaluation of concrete after self-healing with specific criteria should be conducted.

4.2. Real-time tracking and monitoring cracks

It can be seen that the SEM or even CT-scan can not be suitable for simultaneous monitoring of cracks healing as it happens. Strength and water permeability tests need to fragment and elaborately prepare the concrete specimens. Therefore, ultrasonic wave-based technology can be a great way to evaluate self-healing capacity and monitor the healing of cracks in concrete. This technique can be divided into ultrasonic pulse velocity (UPV), acoustic emission (AE), surface-wave transmission, ultrasound diffusivity, coda wave interferometry, and non-linear ultrasonics. Of these, the acoustic wave method can capture the events during the cracking/damaging/loading of concrete. When the crack is only partially healed, it is necessary to combined with effective non-destructive test method since the evaluation of crack healing and the characterisation of the voids can be determined quantitatively.

4.3. Improve the accuracy and reduce noise in measurements

Many experimental studies show that the moisture content, size of the concrete specimens, and rate of application of load can affect the accuracy of the results in both destructive and non-destructive tests. Additionally, the sensitivity to environmental noises and the lack of high signal quality can be the other factors that lead to unexpected effects. At the same time, when the cracks are not uniform and highly random, it is difficult to determine the actual effect of the self-healing process. Experiments have not solved this problem. Although there are many studies in different groups, different scales, and different approaches, when raising the level of testing to realistic structures, many challenges appear. The conditions in the laboratory are no longer guaranteed and maintained in real conditions, and the influencing factors only in real conditions also have a significant impact on self-healing. Environmental conditions such as temperature and humidity have been taken into account and tested at the laboratory scale. However, the weather element is at a different level of impact, both a combination of many factors at the same time impact and a change of irregularity, significantly contributing to the deviations in the measurement, calculation of the self-healing effect.

4.4. Repeatability of self-healing and environmental factors

For the extrinsic method, the ability to repeat and maintain the self-healing effect is an issue that needs to be solved. For example, when using hollow-tube systems in concrete, it is possible to inject repair materials from outside when needed, but it will be easy to clog and have difficulty in the second crack (or more) onwards (if any). Using short tubes, tablets, pellets containing a chemical or mineral solid, the effect may be high and immediate, but the repeatability is very limited. When the chemical reactions form the healing products, the concrete structure will change from the original, respectively, result in the difficulty of the subsequent healing process. That is not considered the adequate time of these chemicals or minerals in concrete; how long can it maintain when cracks appear late or very late in the life cycle of structures and structures.

As for the intrinsic method, the most significant advantage is that self-healing is possible without external intervention. However, it should be clear that the self-healing effect will be related to external environmental conditions such as humidity, temperature, light, pH, or a combination of these factors. Therefore, it is necessary to identify and select the appropriate scope of application for this method. It is not possible to have a high self-healing effect for all specific conditions or structures. Another problem that this method faces is the inconsistent response and the sensitivity to the crack. Actual conditions will lead to cracks appearing in mass with different scales, patterns, positions, and morphology throughout the concrete structures. This matter can easily lead to uneven results or even delay the "feedback" of healing agents to the cracks. Therefore, it is necessary to have solutions or research directions to reduce the dependence or sensitivity to environmental factors and control response sensitivity according to designed calculations. In addition, it is also necessary to consider changing, improving, or applying entirely new construction methods with concrete materials as needed to maximize healing potential. In this trend, 3D concrete printing containing self-healing agents can be considered a promising solution.

5. Conclusions

We have outlined the current research and development of "self-healing concrete" because this topic is progressing rapidly both in Vietnam and overseas. Outstanding issues can be overcome by collaborating and sharing in research across groups. New and multi-viewpoint methods will also be of great help in improving the resilience of concrete. The healing rate of using mineral admixtures like slag and fly ash is very slow and takes a long time, but using these materials is a way to solve the waste for the environment. The high capacity of healing product forming belongs to the combination of bacteria and high-cost nutrients or complicated technologies of carrier production. There will be no comprehensive solution to every problem. Appropriate techniques should be considered, designed, calculated, and chosen for clear and specific purposes and objectives. In general, no single testing method under consideration can give a comprehensive enough tool for self-healing assessment in concrete. Hence, the standard test procedure should combine a certain number of testing methods, including destructive and non-destructive techniques. Above all, ideas such as self-healing/self-repairing of concrete by bacteria have been proposed and promising results. It is on the way to bringing dreams closer to real life, beyond the existing concrete engineering research framework. With more robust focusing and more in-depth knowledge, self-healing/self-repairing can be applied to concrete structures shortly.

References

[1]. M. De Rooij, K. Van Tittelboom, N. De Belie, and E. Schlangen, *Self-healing phenomena in cement-Based materials: state-of-the-art report of RILEM technical committee 221-SHC: self-Healing phenomena in cement-Based materials*, vol. 11. Springer, 2013.

[2]. S. Igarashi, M. Kunieda, and T. Nishiwaki, “Research activity of JCI technical committee TC-075B: Autogenous healing in cementitious materials,” in *Proceedings of 4th International Conference on Construction Materials: Performance, Innovations and Structural Implications*, 2009, pp. 89–96.

[3]. W. Wang, T. Zhong, X. Wang, and Z. He, “Research Status of Self-healing Concrete,” in *IOP Conference Series: Earth and Environmental Science*, 2019, vol. 218, no. 1, p. 012037.

[4]. V. Wiktor and H. M. Jonkers, “Quantification of crack-healing in novel bacteria-based self-healing concrete,” *Cement and Concrete Composites*, vol. 33, no. 7, pp. 763–770, 2011.

[5]. N. N. T. Huynh, K. Imamoto, and C. Kiyohara, “Eco-friendly technique on nutrient sources and capsulation for bacteria-based self-healing concrete,” in *Proceedings of the Japan Concrete Institute*, Hiroshima, 2020, vol. 42, pp. 1288–1293.

[6]. H. N. T. Nguyen, A. T. Nguyen-Phung, and K. S. Nguyen, “Long-term mechanical performance of microbial modified concrete,” presented at the The 7th International Conference of Asian Concrete Federation “Sustainable concrete for now and the future,” Vietnam, Nov. 2016.

[7]. N. N. T. Huynh, N. Q. Nhu, and N. K. Son, “Developing the solution of microbially induced CaCO3 precipitation coating for cement concrete,” in *IOP Conference Series: Materials Science and Engineering*, 2018, vol. 431, p. 062006.

[8]. N. N. T. Huynh, K. Imamoto, and C. Kiyohara, “A Study on Biomineralization using Bacillus Subtilis Natto for Repeatability of Self-Healing Concrete and Strength Improvement,” *Journal of Advanced Concrete Technology*, vol. 17, no. 12, pp. 700–714, 2019.

[9]. W. Yao and W. Zhong, “Mechanism for self-healing of concrete damage,” *Chinese Journal of Materials Research*, vol. 20, no. 1, p. 24, 2006.

[10]. H. M. Jonkers, A. Thijssen, G. Muyzer, O. Copuroglu, and E. Schlangen, “Application of bacteria as self-healing agent for the development of sustainable concrete,” *Ecological engineering*, vol. 36, no. 2, pp. 230–235, 2010.

[11]. E. Schlangen, N. Ter Heide, and K. Van Breugel, “Crack healing of early age cracks in concrete,” in *Measuring, monitoring and modeling concrete properties*, Springer, 2006, pp. 273–284.

[12]. S. S. Lucas, M. Von Tapavicza, A. M. Schmidt, J. Bertling, and A. Nellesen, “Study of quantification methods in self-healing ceramics, polymers and concrete: A route towards standardization,” *Journal of Intelligent Material Systems and Structures*, vol. 27, no. 19, pp. 2577–2598, 2016.

[13]. E. Cuenca, A. Tejedor, and L. Ferrara, “A methodology to assess crack-sealing effectiveness of crystalline admixtures under repeated cracking-healing cycles,” *Construction and Building Materials*, vol. 179, pp. 619–632, 2018.

[14]. H. H. Nguyễn, J.-I. Choi, H.-K. Kim, and B. Y. Lee, “Effects of the type of activator on the self-healing ability of fiber-reinforced alkali-activated slag-based composites at an early age,” *Construction and Building Materials*, vol. 224, pp. 980–994, 2019.

[15]. M. Luo, C. Qian, and R. Li, “Factors affecting crack repairing capacity of bacteria-based self-healing concrete,” *Construction and building materials*, vol. 87, pp. 1–7, 2015.

[16]. S. S. Lucas, C. Moxham, E. Tziviloglou, and H. Jonkers, “Study of self-healing properties in concrete with bacteria encapsulated in expanded clay,” *Science and Technology of Materials*, vol. 30, pp. 93–98, 2018.

[17]. R. A. Khushnood, S. ud din, N. Shaheen, S. Ahmad, and F. Zarrar, “Bio-inspired self-healing cementitious mortar using Bacillus subtilis immobilized on nano-/micro-additives,” *Journal of Intelligent Material Systems and Structures*, vol. 30, no. 1, pp. 3–15, 2019.

[18]. R. Wang, J. Yu, S. Gu, P. He, X. Han, and Q. Liu, “Investigation of self-healing capability on surface and internal cracks of cement mortar with ion chelator,” *Construction and Building Materials*, vol. 236, p. 117598, 2020.

[19]. R. Alghamri, A. Kanellopoulos, and A. Al-Tabbaa, “Impregnation and encapsulation of lightweight aggregates for self-healing concrete,” *Construction and Building Materials*, vol. 124, pp. 910–921, 2016.

[20]. A. Kanellopoulos, T. S. Qureshi, and A. Al-Tabbaa, “Glass encapsulated minerals for self-healing in cement based composites,” *Construction and Building Materials*, vol. 98, pp. 780–791, 2015.

[21]. L. Restuccia, A. Reggio, G. A. Ferro, and J.-M. Tulliani, “New self-healing techniques for cement-based materials,” *Procedia Structural Integrity*, vol. 3, pp. 253–260, 2017.

[22]. P. Azarsa, R. Gupta, and A. Biparva, “Assessment of self-healing and durability parameters of concretes incorporating crystalline admixtures and Portland Limestone Cement,” *Cement and Concrete Composites*, vol. 99, pp. 17–31, 2019.

[23]. N. N. T. Huynh, N. M. Phuong, N. P. A. Toan, and N. K. Son, “Bacillus subtilis HU58 Immobilized in micropores of diatomite for using in self-healing concrete,” *Procedia engineering*, vol. 171, pp. 598–605, 2017.

[24]. N. N. T. Huynh, K. Imamoto, and C. Kiyohara, “Compressive Strength Improvement and Water Permeability of Self-Healing Concrete Using Bacillus Subtilis Natto,” 2020.

[25]. L. Yuan *et al.*, “Research on the Improvement of Concrete Autogenous Self-healing Based on the Regulation of Cement Particle Size Distribution (PSD),” *Materials*, vol. 12, no. 17, p. 2818, 2019.

[26]. N. P. Kaur, J. K. Shah, S. Majhi, and A. Mukherjee, “Healing and simultaneous ultrasonic monitoring of cracks in concrete,” *Materials Today Communications*, vol. 18, pp. 87–99, 2019.

[27]. H. Tanaka, K. Imamoto, and C. Kiyohara, “Fundamental study of a cracked concrete self-repairing system: evaluation of waterproofing performance and filling level of repair agent,” presented at the RILEM Spring Convention and Sustainable Materials Systems and Structures Conference, Croatia, Mar. 2019.

[28]. W. Mao, C. Litina, and A. Al-Tabbaa, “Development and Application of Novel Sodium Silicate Microcapsule-Based Self-Healing Oil Well Cement,” *Materials*, vol. 13, no. 2, p. 456, 2020.

[29]. H. Tanaka, “Improvement effect of concrete durability by crack self-healing system,” Master Thesis, Department of Architecture - Tokyo University of Science, Japan, 2019.

[30]. X. Huang, J. Ge, S. Kaewunruen, and Q. Su, “The Self-Sealing Capacity of Environmentally Friendly, Highly Damped, Fibre-Reinforced Concrete,” *Materials*, vol. 13, no. 2, p. 298, 2020.