Self-Repairing Technique Based on Microcapsules for Cementitious Composites- A Review

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ABSTRACT

Self-repairing technology based on micro-capsules is an efficient solution for repairing cracked cementitious composites. Self-repairing based on microcapsules begins with the occurrence of cracks and develops by releasing self-repairing factors in the cracks located in concrete. Based on previous comprehensive studies, this paper provides an overview of various repairing factors and investigative methodologies. There has recently been a lack of consensus on the most efficient criteria for assessing self-repairing based on microcapsules and the smart solutions for improving capsule survival ratios during mixing. The most commonly utilized self-repairing efficiency assessment indicators are mechanical resistance and durability. On the other hand, Nondestructive methods have been widely used to visualize and assess cementitious composites, self-repairing behavior. However, certain issues remain, such as crack spread behavior, repairing agent kinetics on discrete crack surfaces, and the influence of inserted capsules on the mechanical characteristics of self-repaired cementitious composites, all of which require more investigations.

Keywords: Self-repairing, Micro-capsules, Repairing factors, Investigative methodologies, Nondestructive methods.
تقنية الإصلاح الذاتي المعتمدة على الكبسولات الدقيقة للمركبات الأسمنتية - مراجعة

1. INTRODUCTION

The most important and widely used building material is concrete due to its excellent serviceability, raw material availability, and compressive resistance (Mehta, 1986). Micro-cracks, on the other hand, can significantly compromise the mechanical resistance and durability of concrete elements (Muhammad, et al., 2016). Water and chloride infiltration through cracks has a significant impact on the durability of concrete elements and causes erosion of steel-reinforcement bars, which leads to failure concerns (Milla, et al., 2021). As a result, it is critical to repair or heal these fractures to keep concrete elements functional (Yıldırım, et al., 2015). Because most of these healing procedures are limited by accessibility, expense, location, and environmental issues, cracks can only be fixed manually in rare cases (Vijay, et al., 2017). As a result, self-repairing of cracks has become a need for concrete elements, attracting increasing scientific interest. The autogenously healing phenomenon, on the other hand, was seen in nature for many decades (Jacobsen and Sellevold, 1996), (Bekas, et al., 2016). The autogenous is achieved through the production of CO2 and the continual hydration of anhydrite cement pozzolana binding materials (Jacobsen and Sellevold, 1996), (Huang, et al., 2013) when CO2 and water are available (Cowie and Glasser, 1992). Nevertheless, without additional amendment or enhancement, the efficacy of such repairing actions is rather weak. As a result, different techniques have been developed to increase the behavior of self-repairing (De Belie, et al., 2018), generally by incorporating types of additions like crystalline (Ferrara et al., 2014), (Ferrara, et al., 2016), (Roig, et al., 2015), (Roig, et al., 2016) or mineral admixture (Van, et al. 2012), (Huang, et al., 2014), polymers (White, et
(Dry, 1994), microencapsulation (Zemskov, et al., 2011), (Van, et al., 2011), (Lv, et al., 2013), (Isaacs, et al., 2013) (Gilabert, et al., 2015), (Van, et al., 2015), hollow fiber (Dry, 1994), microorganisms (Khaliq and Ehsan, 2016), and nanoparticles (Perez, et al., 2015) into cementitious materials. Furthermore, Strain Hardening Cement-based Composites (SHCC) with distinctive micro-crack behavior and narrow crack width control characteristics has a lot of potential for crack self-repairing (Zhang, et al., 2014), (Cuenca and Ferrara, 2017). According to Muhammad et al.'s assessment, self-repairing based on microcapsules concrete is may the most successful. In addition, when compared to other traditional techniques, the microcapsules strategy's healing process is more flexible, requiring no extra water, having a shorter curing time, and having repeatable seal-healing activities (Thao, et al., 2009), (Van, et al., 2015), (Van, et al., 2016). Self-repairing which is based on micro-capsules for cement pozzolana binding materials was discovered from the investigation presented by White & co-worker (White, et al., 2001). They suggested a type of crack-self-repairing element with integrated microencapsulation. When this type of microencapsulation is disrupted by crack incursion, it releases a repairing agent that polymerizes with the embedded catalyst to repair and seal the cracks, as seen in Figure 1. Following that, self-repairing based on microcapsules technology for cementitious materials was widely adopted, and it is now widely acknowledged as the most promising method for concrete infrastructure self-healing. Figure 2 depicts a typical arrangement of self-repairing based on microcapsules concrete samples. These capsules are positioned perpendicular to the pre-crack in the test, and they're generally close together with other capsules containing water or accelerator to see how additives affect the self-healing process (Feiteira, et al., 2016).

Figure 1. Self-repairing simplified notion for cementitious materials: (a) crack formation, (b) repairing factors spreading; (c) polymerisation (De Belie, et al., 2018).

The capsules' shells are generally made of brittle materials, and concrete samples could be prismatic, cylindrical, based on the experiment's parameters and techniques used. The quick rupturing of previously placed capsules, the penetration of repairing factors into the crack area, and the subsequent sufficient cure responses are critical to the repairing concept of self-repairing
based on microcapsules concrete (Gilabert, et al., 2017). As a result, these three subprocesses must be triggered as soon as possible to ensure high-efficiency self-repairing (Kessler, et al. 2003).

![Figure 2](image)

**Figure 2.** Arrangement of self-repairing based on microcapsules concrete: (a) capsule fracture due to crack formation; (b) spread repairing factor in crack; (c) curing by repairing factor (Li, et al., 2013).

The composition of repairing factors (Jackson, et al., 2011), (Haase, et al., 2012), (Haiyan, et al., 2012), (Moll, et al., 2013), (Fischer, et al., 2016), accelerators (Van, et al., 2011), (Feiteira, et al., 2016), capsule content (Pye and Beaudoin, 1992), (Li, et al., 1998), (Zhou, et al., 2006), (Thao, et al., 2011) (Van, et al, 2011), reaction conditions (Yuan, et al., 2013), (Jin, et al., 2014), and fracture patterns (Van, et al., 2011), (Van, et al., 2012), (Van, et al., 2013), (Van, et al., 2015) are all elements that impact the curing process of self-repairing based on microcapsules concrete. Furthermore, the experimental procedures used to measure self-repairing effectiveness have an impact on the results (Van, et al., 2011), (Bekas, et al., 2016), (Van, et al., 2016), (Feiteira, et al., 2016). The purpose of this review is to go through several aspects that affect the effectiveness of self-repairing based on microcapsules concrete.

2. Microcapsules-Based Self-Repairing Factors

Most of the repairing factors, in self-repairing which based on microcapsules concrete, are polymer materials (Dry, et al., 2003), (Joseph, et al., 2010), (Van, et al., 2011), (Feiteira, et al., 2016), (Van, et al., 2016), which have the potential capacity for crack repairing, like quick polymerisation (White, et al., 2001), stress transfer capability (Dry, et al., 2003), and low viscosity (Feiteira, et al., 2016). The repairing effectiveness of microcapsules-based self-repairing technologies is closely connected to the behavior and reaction mechanism of repairing factors (Huang, et al., 2014). As a result, the development of a perfect repairing factor takes precedence in investigations on microcapsules-based self-repairing concrete. Table 1 summarizes the repairing factors used by microcapsules-based self-repairing concrete, which are classified into two categories: single component repairing factors and multicomponent repairing factors. Premature chemical interactions among the accelerators and repairing factors before they flow into fractures may be the major constraint for engineering applications using multicomponent repairing factors (Van, et al., 2011), (Gardner, et al., 2014).
Table 1. repairing factors used by microcapsules-based self-repairing concrete.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Self-repairing factors</th>
<th>Width of cracks (μm)</th>
<th>Duration of curing</th>
<th>Mechanical recovery</th>
<th>Mechanism of self-repairing</th>
<th>Disadvantages</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multicomponent</td>
<td>PU</td>
<td>225-300</td>
<td>—</td>
<td>35-80%</td>
<td>In a wet environment, polymerization is increased.</td>
<td>Premature reaction</td>
<td>(Van, et al., 2011), (Feiteira, et al., 2016), (Van, et al., 2012), (Maes, et al., 2014), (Feiteira, et al., 2017), (Minnebo, et al., 2017).</td>
</tr>
<tr>
<td>Single component</td>
<td>PU</td>
<td>250</td>
<td>—</td>
<td>35-80%</td>
<td>Polymerization in wet environment.</td>
<td>Detachment from the fracture face; load-concentration at the interface.</td>
<td>(Van, et al., 2016), (Van, et al., 2013), (Dunhill, 2016), (Van den, et al., 2016).</td>
</tr>
<tr>
<td>Single component</td>
<td>ER</td>
<td>300</td>
<td>100 minutes</td>
<td>30%</td>
<td>Harden when pressured or heated.</td>
<td>Long duration curing; high viscosity</td>
<td>(Nishiwaki, et al., 2006), (Thao, et al., 2009).</td>
</tr>
<tr>
<td>Multicomponent</td>
<td>ER</td>
<td>225-300</td>
<td>24 hours</td>
<td>35-80%</td>
<td>Rapid hardening with reduced viscosity.</td>
<td>harden and insufficient mixing.</td>
<td>(Nishiwaki, et al., 2006), (Haiyan, et al., 2012), (Van, et al., 2012), (Yuan, et al., 2013), (Li, et al., 2013).</td>
</tr>
<tr>
<td>Single component</td>
<td>CA</td>
<td>&lt;100 seconds</td>
<td>—</td>
<td>—</td>
<td>After tracing hydroxide ions, fast anionic polymerization occurs.</td>
<td>Demand for oxygen and water; repaired cracks were restricted to 100 μm.</td>
<td>(Li, et al., 1998), (Joseph, et al., 2010), (Gardner, et al., 2014).</td>
</tr>
<tr>
<td>Single component</td>
<td>Na₂SiO₃</td>
<td>40</td>
<td>—</td>
<td>20-26%</td>
<td>C-S-H gels are made by reacting Ca(OH)₂ with Na₂SiO₃.</td>
<td>Mechanical recuperation ability is limited.</td>
<td>(Mostavi, et al., 2015)</td>
</tr>
</tbody>
</table>
2.1 Polyurethane repairing factor:
The crack-repairing process is aided by a polyurethane-based repairing factor that foams and expands when a chemical reaction occurs. Because the expansion may seal bigger cracks, a small amount of repairing factor is sufficient for massive crack repairing (Van, et al., 2011). Van & co-workers (Van, et al., 2016) demonstrated that the polymerization reaction required just a little amount of moisture in the cementitious materials, making polyurethane a versatile repairing factor. They also discovered that more than fifty percent of the original resistance and stiffness may be restored, and the water permeability is significantly reduced following polyurethane self-repairing (Van, et al., 2011), as evidenced by neutron radiography visualization data (Zhang, et al., 2014). For initial fractures with widths of one hundred and three hundred microns, Maes & co-workers (Maes, et al., 2014) discovered that polyurethane can minimize chloride penetration along the crack route by seventy-six and thirty-three percent, respectively. Many investigations (Maes, et al., 2014), (Van, et al., 2015), have confirmed the self-repairing efficacy and benefits of the polyurethane repairing factor. As a result, current studies on polyurethane-based repairing factors focus on establishing the particular characteristics needed to achieve great repairing results, such as the accelerator, appropriate viscosity, stiffness, Young's modulus, interface qualities, strain capacity, and bonding strength. Feiteira & co-workers (Feiteira, et al., 2016) investigated the strain-capacity of cured polyurethane-based polymers under repeated load (ACI 224R, 2001), (BS, 2013), taking into account elongation deformation of fatigue-cracks. They discovered that a polyurethane-based repairing factor with an extremely-low viscosity (two hundred millipascal second) may fulfill strain capacity requirements of fifty to hundred percent and decrease failures caused by foam structure breakup, and these results have been approved by Feiteira & co-workers (Feiteira, et al., 2017). Furthermore, they claimed that flexible polymer materials with Young’s modulus less than 10 MPa may resist cracks spread, arrest new cracks from forming, and minimize interface stress, reducing bonding detachment. Dry et co-workers (Dry, et al., 2003), on the other hand, discovered that the modulus of elasticity of adhesives-repairing factor may impact its capacity to repair. They reported that low stiffness might lead to low recovered stiffness values, while a stiff adhesive can simply transmit stress through cracks, enabling the cracks to continue to grow. However, Gilabert et al. (Gilabert, et al., 2017) used tensile testing to assess the resistance contribution of a cured polyurethane-based repairing factor, and postulated a linear relation between the crack-opening size (COS) and the ultimate tensile strength. The ultimate stress varied from 3.7 MPa for a COS of 50.8 micrometers to 1.2 MPa for a COS of 381 micrometers. Despite the fact that several investigations were done to enhance the self-repairing effectiveness of

<table>
<thead>
<tr>
<th>Multicomponent</th>
<th>MMA</th>
<th>24 hours</th>
<th>Thermodynamically induced molecule inter-diffusion</th>
<th>premature matrix absorption</th>
</tr>
</thead>
</table>

*PU: Polyurethane; ER: Epoxy resin; CA: Cyanoacrylate adhesives; Na₂SiO₃: Sodium silicate; MMA: Methyl methacrylate
polyurethane repairing factors, there is still no consensus on particular self-repairing efficiency assessment criteria. More controversially, four point flexural results for the microencapsulated polyurethane-based repairing factor, in large-scale concrete beams, are even varied due to exposed crack interfaces and insufficient amount of repairing factor (Karaiskos, et al., 2016). Figure 3 depicts the polyurethane-based repairing factor's capacity to recover mechanical characteristics. Basically, within the first or second stages of reloading, the variance in restored mechanical resistance is significantly smaller than that of regained stiffness. The effectiveness of regained stiffness has been investigated by Minnebo (Minnebo, et al., 2017). They reported a 104 percent through the second reloading, and this result was greater than Van et al.'s result (Van, et al., 2011) by 50 percent.

![Figure 3](image)

**Figure 3.** Comparative on self-repairing effectiveness of polyurethane repairing factors (Van, et al., 2012), (Minnebo, et al., 2017).

### 2.2 Epoxy resin repairing factor

Epoxy resin (ER), which may be hardened by pressurization or heating, is another early repairing factor (Blaiszik, et al., 2009). Thao & co-workers (Thao, et al., 2009) used glass tubes to embed ER in a steel-mesh-reinforced mortar sample, resulting in a thirty percent increase in resistance relative to the initial resistance following repeated autonomic repairing. Despite the high self-repairing outcome provided by the rapid hardening reaction of ER in a sophisticated heating self-repairing system for concrete described by Nishiwaki (Nishiwaki, et al., 2006), the curing process required approximately 100 minutes due to the high viscosity of this type of repairing factor. As a result, current studies into ER repairing factors have focused on decreasing the duration of curing by including accelerators, which known as multiple-components ER repairing factor. Li (Li, et al., 2013) used polyether-amine as a hardener of repairing factors to improve repairing efficiency in polymer. Moreover, other studies found that diluting this type of ER improved the repairing process. Van (Van, et al., 2011) combined epoxy with methyl-methacrylate to create a repairing
factor with reduced viscosity and observed a significant increase in water permeability. They also used two-component repairing factors made from polyurethane and ER from two different tubes to speed up the polymerizing procedure. Thao (Thao, et al., 2011) showed that an epoxy-polymer with low viscosity (two hundred and fifty to five hundred millipascal second) may flow easily through cracks and repair quickly, but the precise viscosity still has to be studied further.

2.3 Cyanoacrylate Repairing Factor

The self-repairing chemical cyanoacrylate, which is found in hollow glass fibers, was first employed as superglue to patch cracks in cementitious materials. According to Li (Li, et al., 1998), the elastic-modulus recovery of SHCC reinforced beams under cyclic loading was used to assess the self-repairing efficiency of cyanoacrylate, however the thickness of repaired cracks was restricted to fifty micrometers. Although the low viscosity of the repairing factor aided the quick curing process (in seconds) when moisture and oxygen were present, the fracture repairing ability was limited to less than a hundred micrometers because of the capillary needed (Gardner, et al., 2014). Short setting times, might result in inadequate permeation of the repairing factor in the cracks, resulting in un-reacted cyanoacrylate in the capsule. Moreover, Lark (Joseph, et al., 2010) showed that the remaining cyanoacrylate may stay liquid for up to seven days, possibly indicating a tertiary repairing effect, which Gardner (Gardner, et al., 2014) verified. The high bonding strength among cured cyanoacrylate and the fracture surfaces, compared to other repairing factors, can inhibit new crack development during reloading, and the process of curing could be expedited via the alkaline environment conditions (Li, et al., 1998), (Joseph, et al., 2010), (Gardner, et al., 2014).

2.4 Na$_2$SiO$_3$ Solution Repairing Factor

When Na$_2$SiO$_3$ solution interacts with Ca(OH)$_2$ in cementitious materials, calcium-silicate hydrate (CSH) gels are formed to repairing cracks. Gilford & co-worker (Gilford, et al., 2014) observed an enhancement of eleven percent in Young’s modulus of concrete after being repaired by Na$_2$SiO$_3$ packed with microcapsules. However, Mostavi (Mostavi, et al., 2015) created a double-shelled microcapsules contained Na$_2$SiO$_3$, and focused on the capsules’ performance. Because the concentration of Na$_2$SiO$_3$ solution affects self-repairing efficiency, the exhaustion of repairing factors and poor mechanical resistance may limit the engineering use of Na$_2$SiO$_3$ solution (Li and Hou 2005), (Leung, et al., 2011).

2.5 Methyl methacrylate Repairing Factor

Few researches have used methyl methacrylate as a repairing factor. Diry (Diry, 2000) observed the effective spread of methyl methacrylate from fibers into cement, after exposed to heat, and achieved favorable concrete permeability results. Yang & co-workers (Yang, et al., 2011) developed a novel form of self-repairing material by microencapsulating methyl methacrylate in a silica gel shell and observed an enhancement in the gas permeability test. Van (Van, et al., 2013), on the other hand, filled the methyl methacrylate in borosilicate capillary glass-tubes and found no
enhancement in the water ingress test when compared to the untreated fractures. The cause for this might be due to the repairing ingredient in the capsules curing too quickly.

3. ASSESSMENT OF SELF-REPAIRING EFFICIENCY

3.1 Restoring of durability

The basic objective of self-repairing concrete is to promote durability recovery, which defines the indication for self-repairing efficiency evaluation. When evaluating the durability of concrete infrastructure, fluid permeability is a direct indicator of concrete's service life (Li, et al., 2013), (Huang, et al., 2016), (Milla, et al., 2021). As a result, the most often used method for determining the durability of self-repairing concrete is the permeability test. The setup and technique for the permeability test were described in detail by Van & co-workers (Van, et al., 2011). The coefficient of permeability is computed quantitatively utilizing Darcy's law by measuring the drop in water column with time, as shown in Figure 4a. This method has been used extensively to assess the repairing effectiveness of single pre-oriented cracks, demonstrating that the microencapsulation procedure is extremely successful in restoring durability. Van & co-workers (Van, et al., 2011) examined water permeability reductions in concrete with cured fractures, and the findings ranged from one hundred and to ten thousand for concrete beams containing various capsules. Nevertheless, in the large-scale lab test with many fractures shown in Figure 4b, evaluating the repairing effectiveness and measuring the permeability of each fracture is challenging (Van, et al., 2015), (Van, et al., 2016). The capillary absorptivity appears to be more reliable than the permeability test in determining the durability of crack-repairing concrete in unsaturated condition (Van, et al., 2013), (Van den, et al., 2016), (Van Belleghem, et al., 2016). Gravimetric analysis has been widely used in the past to easily compute the quantitative capillary absorption value, but it is unable to depict the spatial distributions of water (Feiteira, et al., 2016). To acquire characteristics of water distribution inside discrete fractures, X-ray computed scanning and neutron radiographic methods were used. Van (Van, et al., 2013) initially used neutron radiographic to observe the moisture absorption of various samples as well as the water distribution on repaired fracture surfaces, and they looked at the influence of viscosity on self-repairing ability (Van den, et al., 2016). Although the accuracy of neutron radiographic are excellent, the test's expensive cost prevents it from becoming more widely used. As a result, using a low-cost X-ray radiographic approach to test the durability of crack-repairing concrete may be cost-effective (Van Belleghem, et al., 2016). Few investigations have looked into chloride diffusion of microcapsules-based self-repairing concrete in regards to permeability or capillary absorption of water. Maes (Maes, et al., 2014) used an acid-soluble chloride -extraction test to investigate self-repairing capability and discovered that microencapsulated polyurethane can inhibit chloride spreading from cracks with widths ranging from one hundred to three hundred micrometers. Nevertheless, because of the weaker capillary strength among fracture surfaces than in capsules, inadequate repairing response generates significant chloride permeation in big cracks (Joseph, et al., 2010). Furthermore, Yang & co-workers (Yang, et al., 2011) focused on the permeability of gas and
discovered that oil-core/silica-gel shell micro-capsules reduced the permeability of gas by roughly 50.2 percent for self-repairing cement paste.

Figure 4. Restored mechanical characteristics of self-repairing concrete with various cyclic reloading: (a) single fracture; (b) multiple fracture (Dry, 1996).

3.2 Mechanical Characteristics Restoring
When the self-repairing action begins and the repairing factor has fully hardened, the self-repairing concrete is reloaded and tested for resistance, toughness, and stiffness using three or four-point flexural methods that rely on stress–strain ratios or load–displacement relations. Van & co-workers (Van, et al., 2011) compared the mechanical loading relations of untreated, conventionally cured, and autonomously repairing techniques to determine the self-repairing effectiveness of microcapsules-based self-repairing concrete. In Figure 5, the ultimate-strength and slope of the load–displacement ratio relate to strength and stiffness indicators, correspondingly, demonstrating the recovering effectiveness of mechanical characteristics for autonomous repairing concrete.
Feiteira & co-workers (Feiteira, et al., 2016) used a 3-point flexural test to investigate the load-displacement relationship of fracturing and fracture spreading cycles in repairing and non-repairing samples containing micro-capsulated polymer precursors. They only got a thirty percent mechanical stiffness recovering for each thirty days with thicknesses approximately twenty micrometers due to the poor stiffness of the polymers utilized. Likewise, Thao & co-workers (Thao, et al., 2009) discovered a thirty percent grow in resistance with repeated cyclic loads compared to the initial resistance. For another mechanical studies (Van, et al., 2012), the microcapsules-based self-repairing approach restored almost eighty percent of the actual resistance and stiffness. The recovering capability of mechanical resistance might also be greatly impacted by fracture modes, even with the identical repairing factors and capsules. For instance, in the case of self-repairing concrete with many cracks, the 4-point flexural test fails to produce satisfactory results in terms of mechanical resistance recovering capability (Van, et al., 2016). Dunhill (Dunhill, 2016) also found some surprising mechanical recovery findings for a concrete beam exposed to a 4-point flexural force.

3.3 Conception of Self-Repairing Action

High resolution x-ray computed tomography (HRXCT), digital image correlation (DIC), fluorescence microscope, and photomicrograph are prevalent techniques gives magnified conception for the behavior and action of self-repairing concrete like width of fracture, place of micro-encapsules, and spreading of repairing-factor. Van & co-workers (Van, et al., 2016) used all of the mentioned-above methodologies to analyze and assess the self-repairing activity of polyurethane repairing factors. Figure 6 shows a summary of the various outcomes. Digital image correlation technique is most commonly used to examine fracture modes in the surfaces of concrete samples (Xiao, et al., 2012), (Li, et al., 2012), (Zhu, et al., 2020), (Ahn, et al., 2021). According to the digital image correlation data in Figure 6a, a greater fracture mode appeared in the concrete beam's center section. Feiteira & co-workers (Feiteira, et al., 2017) employed digital image correlation to track the fracture opening over the whole length of the fracture, and they found a
rather serious fracture widening-process when stiff polymers were used as the repairing factor. To analyze the position and state of capsules, X-ray scanning was used to get 3-dimensional imaging of the inside component of concrete. The micro-capsules were roughly thirteen millimeters under the upper surface of the sample, as seen in Figure 6b. Because of the inadequate capillarity load, the micro-capsules are not entirely emptied, and the repairing factor within the fracture distributes unevenly. Gilabert & co-workers (Gilabert, et al., 2017) validated the same finding utilizing micro computed tomography analysis. Van & co-workers (Van, et al., 2015) found that if a fracture propagates because the presence of capsule, is reliant on chance, except when the cement paste operates as weak areas between the capsule and the mixture and promote the fracture formation, dependent on X-ray radiography of concrete beam samples with actual cracks. Electron microscopic visualization methods are commonly used to quantify the fracture size and observe the repairing factor distribution, as illustrated in Figure 6c. According to the results, the beam with micro-capsulated polyurethane has the best percentage of fracture sealing and the greatest ability to repair bigger fractures with a width of one hundred and ninety-eight micrometers.

Figure 6. Conception of self-repairing fractures in concrete by various techniques: (a) DIC; (b) X-ray scanning; (c) electron microscopic visualization (Van, et al., 2015).
4. CONCLUSION:

Microcapsules-based self-repairing method has shown to be a successful way for concrete fracture repair. Microcapsules-based self-repairing method relies heavily on repairing factors and encapsulation processes. Several experimental investigations have been conducted to assess the efficacy of the self-repairing approach. The following are the associated conclusions and recommendations:

- Polyurethane polymer is the most effective of all existing self-repairing factors, with excellent flexibility, a comparably quick curing duration, and a self-repairing mechanism that does not require water. Applied stress near the interface, separation of hardened self-repairing factor, insufficient blending, and early response all require additional adjustments.

- It's hard to identify the most accurate and trustworthy effectiveness analytical approach for self-repairing performance since there aren't any standardized self-repairing effectiveness characteristics or assessment methods. Mechanical testing and permeability measurements are commonly used to evaluate the effectiveness of microcapsules-based self-repairing concrete. Methods including digital image correlation, High resolution x-ray computed tomography (X-ray CT), and neutron tomography, might help researchers understand better self-repairing processes.

More studies are needed in terms of determining the appropriate viscosity, elastic module fit, strain capacity, and binding force of polyurethane polymers repairing factors. Aside from capsules content and repairing factors, more investigation into the fracture growth behavior of self-repairing which is based on micro-capsules for cement pozzolana binding materials, the kinetics of repairing factors in discrete fracture surfaces, and other thorough aspects is needed.

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