A novel method of adding aluminum oxide to improve the efficiency of bio-remediation was evaluated. Aluminum oxide, at various amounts, was added to the medium to obtain a change in pH and urease activity. Urea and calcium salts with various amounts of aluminum oxide, were mixed with an absorbance-fixed bacterial suspension to analyze the effect of the method on production rates for calcium carbonate. Concrete specimens in which precracking was induced were subjected to bio-remediation with different amounts of added aluminum oxide. Adding aluminum oxide can decrease the pH of the environment, providing a more suitable micro environment and improving urease activity of bacteria. Moreover, the method can increase the adsorption of germs to increase the utilization rate of urea and production rate for calcium carbonate. After repairing, those with added aluminum oxide were better repaired and their strengths were higher. Therefore, the method can accelerate the bio-remediation reaction and reduce repairing time.
enzymatic hydrolysis of urea is catalyzed by the microbially produced enzyme urease and calcium carbonate precipitation can be obtained in the presence of calcium ions (Sun et al. 2018a; Sun et al. 2018b; Sun and Miao 2018; Stocks-Fisher et al. 1999; Zhu and Dittrich 2016). The precipitated calcium carbonate has a cementing effect that can be used to seal the cracks and enhance the properties of concrete (Schlangen and Sangadji 2013). Several studies have also analyzed potential improvements in the durability of concrete with MICP technology (Tittelboom et al. 2010; Achal et al. 2015; Bang et al. 2010; Muynck et al. 2008; Pacheco-Torgal and Labrincha 2013; Tziviloglou et al. 2016). There are two ways to carry out bioremediation in concrete specimens. In the first, bacterial cells (with appropriate nutrition, urea and a calcium source) are incorporated into the concrete matrix during casting and upon the appearance of cracks, biominerals form calcite that seals the cracks (Wang et al. 2012). In another method, bacterial cells are applied on the surface concrete cracks. The MICP based bioremediation of concrete specimens was initiated by Ramachandran et al. (Ramachandran et al. 2001). Crack sealing by calcite precipitated by bacteria on concrete resulted in reduction in water permeability and crack bridging was demonstrated by an increase in ultrasonic pulse velocity (Sierra-Beltran et al. 2014). Wang et al. (2012) evaluated bioremediation efficiency by means of strength regain in mortar prisms and a decrease in water permeability in concrete cylinders. The presence of calcite in the repair material was determined by performing thermogravimetric analysis (Sierra-Beltran et al. 2014). An on-site application of MICP based bioremediation was successfully employed to treat the damaged ramps of parking garages in Breda, Netherlands by spraying bio-based repair solution (Wiktor and Jonkers 2015).

When bacterial cells are added in the crack, they can grow in the presence of water or oxygen followed by urease production and ultimately calcite precipitation that seals the cracks (Achal and Mukherjee 2015). An obstacle faced during crack healing of cementitious materials is the high pH of cement. However, these proposed methods are complicated to adopt and have high associated costs (the cost of microcapsules is around 10 US dollars/500 g), meaning they are not suitable for practical engineering applications. Therefore, a more economical method needs to be presented. As pH at the surface of the crack becomes lower than 10 after several days (Pu et al. 2012), it is of great importance to reduce the initial pH of the environment before repairing cracks. In this paper, a method of adding aluminum oxide (Al$_2$O$_3$) in cracks was used and the repairing effect was evaluated after bio-remediation. Before repairing cracks in concrete, the pH of the medium, urease activity and productive rates for calcium carbonate were used to evaluate the influence of Al$_2$O$_3$ on the MICP process. During repair of concrete cracks, pH of the leachate and urea utilization were measured and repairing the cracks, sonic time values, and productive rates for calcium carbonate and strength were used to study the repairing effect of this method (adding Al$_2$O$_3$ in cracks). As a consequence, this study provides an important reference for subsequent practical engineering applications.

2. Materials and methods

2.1 Biological material and aluminum oxide

In this paper, Sporosarcina pasteurii ATCC 11859 (from the Guangdong culture collection center of China) was cultured on Luria Bertani medium (yeast extract 15.0 g/L, polypeptone 10.0 g/L, NaCl 10.0 g/L, and distilled water). Cultures were incubated at 30°C with shaking at 100 rpm.

Aluminum oxide is a chemical compound of aluminum and oxygen with the chemical formula Al$_2$O$_3$. Aluminum oxide is used to produce aluminum metal, as an abrasive owing to its high hardness (Campbell et al. 1999). Aluminum oxide is manufactured from aluminum hydroxide by dehydroxylation in a way that produces a highly porous material (Choi et al. 2012), therefore, the material can absorb bacteria and is an excellent bacterial carrier that allows more carbonate precipitation in cracks. There are two more reasons why Al$_2$O$_3$ (CAS NO. 1344-28-1) pretreated with acidic solvent was used in this study. One was that the material can decrease the pH of the solution in cracks. The other reason was its weak cationic characteristics, which allow it to easily retain negatively charged substances (e.g. S. pasteurii) on the surface (Yang and Cheng 2013).

The cost of aluminum oxide is about 1.7 US dollars/500 g, significantly cheaper than other methods, therefore, the method proposed in this study is cost-efficient.

2.2 pH and Enzyme activity

(1) Measurement of enzyme activity

6 mL of bacterial suspension was mixed with 54 mL of urea solution (1 mol/L) and the electrical conductivity was measured every 5 min. The average change in con-
ductivity per minute (ms/min) was calculated and corresponded to 11 mM urea hydrolyzed/min. Therefore, the change in conductivity per minute (ms/min) can be converted to the amount of urease hydrolysis per unit time. This can be further converted to the rate of hydrolysis of urea per minute (mM urea hydrolyzed min⁻¹) by multiplying by a dilution factor of 10, which represents enzyme activity (Whiffin 2004).

(2) Changing rules of pH and enzyme activity
The initial pH value was 10 and various amounts of Al₂O₃ (0, 2 g, 4 g and 6 g) were added to the medium before inoculation with the bacterial culture at a final concentration of 1%. The number of inoculated microbes greatly impacts their growth (Khan and Amarakoon, 2015), therefore, bacteria were inoculated at the same OD₆₀₀ value (0.871). During 72 h of culture, the pH of the medium and enzyme activity of the bacteria were monitored every day. Triplicate samples were prepared to determine the standard deviation and average values were calculated.

2.3 Comparative tests of precipitation rates for calcium carbonate
This set of tests examined the effect of Al₂O₃ on the rate of urea hydrolysis. For this purpose, the amount of calcium carbonate precipitated from an equimolar solution of urea-Ca(CH₃COO)₂, with concentrations of 0.5 M and with an original pH of 10, was evaluated. Calcium carbonate produced from calcium chloride is calcite, while it is aragonite with calcium acetate, which had a greater bonding effect than calcite under solution conditions (Tittelboom et al. 2010; Cölfen and Antonietti 1998; Muynck et al. 2008). In addition, Zhang et al. (2015) drew the conclusion that the pore size distribution in microbial mortar treated with Ca(CH₃COO)₂ was much more uniform than when CaCl₂ or Ca(NO₃)₂ were used. Calcium acetate was used as a calcium recourse in the mixed solution instead of calcium chloride. The absorbance of the bacterial suspension used here was constant and equal to 0.975. The solutions of urea-Ca(CH₃COO)₂ were thoroughly mixed with water in order to ensure that the chemical products were completely dissolved. Twelve samples were made in a sterile manner, which were further divided into four groups according to the amount of Al₂O₃ added (0, 2 g, 4 g and 6 g). Every group consisted of three replicates. After adding Al₂O₃ to the urea-Ca(CH₃COO)₂ solution, 15 mL of bacterial suspension and 15 mL of urea-Ca(CH₃COO)₂ solution were mixed in 100 mL transparent beakers, resulting in a final volume a 30 mL. Al₂O₃ is soluble in alkaline solution, but at a pH of 10 the amount of OH⁻ in solution was small, therefore, the consumption of Al₂O₃ can be ignored. After 2 and 4 days, the amount of precipitated material was evaluated as follows: (i) the solution was filtered through filter paper; (ii) the paper filter and the transparent beakers were dried and the amount of deposited particles was evaluated; (iii) the total amount of CaCO₃ is calculated from the difference between the amount of the material deposited on the filter paper and in the transparent beaker and the amount of Al₂O₃ added. The evaluation criterion was the precipitation rate of calcium carbonate, i.e., the ratio of the actual amount of calcium carbonate produced to the theoretically calculated amount.

2.4 Cement concrete specimen
C50 concrete specimens were prepared and relevant components are shown in Table 1. The cement was P.O 42.5. The sand used in tests had the following characteristics: medium sand with uneven grading, a fineness modulus of 2.34, specific gravity of 2.65 (Gₛ = 2.65), coefficient of curvature of 0.97 (Gₖ = 0.97), coefficient of uniformity of 1.35 (Gₜ = 1.35) and d₅₀ = 0.45 mm. The stone used was basalt with grain size of 5 ~ 15mm.

The concrete specimens were cast in 100 × 100 × 100 mm molds. Three cracks with length of 5 cm and depth of 10 cm were made using stainless steel sheets of different thicknesses (1.0 mm, 1.5 mm and 2.0 mm). 27 samples were made with various crack widths and three more samples without cracks were used as a control group. In each group, three of the samples were remediated by the addition of Al₂O₃ and three without adding Al₂O₃, while the other three were not remediated for comparison. The amount of Al₂O₃ was 6 g, 9 g and 12 g, respectively corresponding to different crack widths for the same void ratio.

2.5 Repairing method with MICP technology
After 28 days of standard curing, a bacterial suspension and gelling solution (mix of calcium acetate and urea solution, with concentrations of 0.5 M each) were used to repair cracks in concrete specimens. The standard curing conditions for all specimens were moist conditions (RH > 98%) at 23 ± 2°C for 28 days. Geotextile was put under the concrete specimens, preventing bacterial suspension and gelling solution from leaving the cracks rapidly and ensuring their adequate retention in the cracks. The bacterial suspension and gelling solution were injected into the cracks at the speed of 1 mL/min using a peristaltic pump. The speed allowed solution to slowly pass through the crack and to ensure better treatment. During the bio-remediation process, the three cracks in each specimen were cured at the same time. The total volume of bacterial solution mixed with gelling solution was 30 mL, 45 mL and 60 mL corresponding to different crack widths of 1.0 mm, 1.5 mm and 2.0 mm, respectively. The bacterial suspension and gelling

![Table 1 The ratio of concrete specimen (kg/m³).](image-url)
solution were added once per day. The repairing period was 9 days, following which the repaired concrete specimens were dried indoors for subsequent tests.

In this study, although ordinary crystallization precipitation may cause a partial reparative effect, it is a natural phenomenon and the impact was negligible. Therefore, the repaired cracks can be seen as the sole result of MICP technology.

2.6 Evaluation of repairing effect
(1) pH and urea utilization in the leachate
The bacterial suspension was added every day and the leachate was obtained. The pH of the leachate was measured to obtain changes in pH during the 9-day repair process.

Urea utilization in the leachate was indicated by the amount of urea decomposed by bacteria in the urea media, which was determined by the total ammonium nitrogen (TAN) in the urea media (Wang et al. 2012). One mole of urea (CO(NH2)2) produces 2 moles of NH4. The amount of NH4 indicates the amount of urea decomposed. TAN concentrations were measured calorimetrically using the method of Nessler (Ivanov et al. 2005).

The amount of urea decomposed every day was calculated based on the TAN values measured in the urea media.

(2) Sonic time values obtained through ultrasonic testing
As the height of concrete specimen was 100 mm, measuring points perpendicular to the crack were located at 25 mm, 50 mm, and 75 mm from the bottom of the specimens to obtain sonic time values. As a sudden decrease in sonic time values occurs between repaired and unrepaired sections, the repairing effect of the crack could be determined by comparing sonic time values.

(3) Unconfined compressive strength tests
The unconfined compressive strength (UCS) is an indicator used to study the mechanical properties of repaired concrete (Wang et al. 2012). Specimens were placed vertically along the crack to conduct unconfined compression tests. The failure modes of the samples were established as brittle fracture modes and the maximum values were obtained as their UCS values.

3. Results and discussion

3.1 Changing rates of pH and enzyme activity
pH has an impact on the growth of S. pasteurii (Whiffin 2004) and the addition of Al2O3 neutralizes the alkalinity of the medium, therefore, it was important to know the effect of adding Al2O3 on the pH of medium and the urease activity of the bacteria.

During the 72 h of culture, the enzyme activity of the bacteria was also monitored every 24 h, as shown in Fig. 2. Adding Al2O3 significantly improved the enzyme activity of the bacteria due to a more suitable growth environment resulting from a decrease of the pH value. Moreover, the larger the amount of alumina, the higher the urease activity. However, on the 4th day, the urease activity decreased rapidly with the addition of 6 g of Al2O3, which was because the bacteria had high urease activity for the first three days, consuming a large amount of nutrients in the medium.

3.2 Comparative tests of precipitation rates for calcium carbonate
MICP has been studied extensively due to the production of calcium precipitate (Ivanov and Chu 2008). Many factors have been shown to impact the type and amount of carbonate precipitation, e.g., the functional attributes of the precipitating microorganisms, the rate of urea hydrolysis, urea and calcium dosages, and the presence of amino acids such as glutamic acid (Whiffin 2004; Hammes et al. 2003a; Rodriguez-Navarro et al. 2003b).
of the concrete specimens without the addition of Al2O3, indicating that the cracks were not well repaired. Cracks with a width of 1.0 mm were repaired more completely, and there was more white calcium carbonate precipitation at the bottom. Compared with cracks of 1.0 mm, the quality of calcium carbonate precipitation decreased with increasing crack width, especially for the width of 2.0 mm. Generally, the time used to repair cracks with a width greater than 1.0 mm was much longer than 9 days (Stuckrath et al. 2014; Alazhari et al. 2018; Khaliq and Ehsan 2016), therefore, there were still some small pores in the cracks due to incomplete filling with calcium precipitation.

Specimens, regardless of the self-healing agent used, showed a pH greater than 12 on the entire surface exposed by the crack (Stuckrath et al. 2014). The pH was an important factor for repairing cracks with the MICP method. Leachate after adding gelling solution was collected every day and its pH values were measured. The average pH values are shown in Fig. 5.

From the specimens without the addition of Al2O3, at the beginning, the pH of the leachate from those cracks wider than 2.0 mm was the lowest, but still higher than 11, which is not a suitable environment for most bacteria (Whiffin 2004). The pH value of the leachate dropped with increasing crack width, which was mainly because the crack width affected the carbonation depth of the concrete (Pu et al. 2012). After that, more and more bacteria adhered to the internal side of the crack as a thin calcium carbonate layer was generated on the surface of the cracks. Moreover, a large amount of the calcium carbonate produced in the crack further reduced the permeability and pH, which was more suitable for the growth of bacteria in the cracks. The pH eventually became stable, at about 9.0, despite the different crack widths.

As for the specimens without the addition of Al2O3 in cracks, at the beginning, the pH was significantly decreased by the dual action of carbonation and Al2O3, therefore, the initial pH of leachate was much lower than those without added Al2O3. The pH values of the leachate were smaller from cracks with a width of 2 mm because the amount of Al2O3 added was larger. However, with the MICP reaction, a large amount of calcium ions participated in the reaction, resulting in more acetate ions binding to hydrogen ions and more hydroxide ions exiting the solution, further increasing the pH. This explains why the pH of the leachate from specimens with crack widths of 2 mm increased slightly and finally tended to be stable.

Therefore, adding Al2O3 in cracks allowed initial pH to remain below 10, which had a significant positive influence on the MICP reaction to improve the efficiency of bio-remediation.

Similar to the pH of the leachate, urea utilization was calculated every day and the average values are shown in Fig. 6. Compared to those without added Al2O3, samples with added Al2O3 to the cracks not only had higher
initial urea utilization rate, but the increasing speed of the utilization rate of urea was larger. Moreover, the utilization rate of urea with added Al$_2$O$_3$ became stable earlier and the eventual values were higher than those without added Al$_2$O$_3$. This was because adding Al$_2$O$_3$ decreased the pH of the solution in the cracks and improved the microenvironment for MICP. In addition, Al$_2$O$_3$ provided a large number of micro-voids (Choi et al. 2012), which allowed a large number of bacteria to adsorb and be retained in the cracks, further improving the urea utilization rate. The improvement of the crack environment was affected by the pH of the solution in the cracks and the number of the bacterial adsorption sites, which were both determined by the amount of added Al$_2$O$_3$. Therefore, with increasing amount of added Al$_2$O$_3$, the urea utilization rate increased significantly.

When it came to samples without added Al$_2$O$_3$, the urea utilization rates were much smaller due to the high pH in the crack, with very little urea decomposed. At a crack width of 2.0 mm, the initial pH was slightly higher, leading to a higher urea utilization rate. However, after that, the number of bacterial adsorption sites became the main factor to determine the utilization rate of urea, so utilization rates of urea with a crack width of 1.0 mm

![Fig. 4 Comparison of the bottom surface of repaired specimens and unrepaired specimens.](image)

![Fig. 5 The pH of the leachate.](image)
grew distinctively and surpassed the other two conditions with smaller crack widths, which provided more bacterial adsorption sites.

Therefore, adding Al\textsubscript{2}O\textsubscript{3} in to the cracks significantly increased the initial urea utilization rate and caused the utilization rate to remain high, producing more calcium carbonate precipitation, which also had a positive influence on the MICP reaction.

### 3.4 Comparison of Sonic time values

De Rooij \textit{et al.} proposed that concrete could heal itself against small microcracks with widths between 0.05 mm and 0.10 mm. Autogenous healing involves both the hydration of unreacted cement, leaching and carbonation of the cement paste (Lors \textit{et al.} 2017). But autogenous healing cannot repair wide cracks. Therefore, bio-remediation method was used here to improve crack repair. Sonic time values were measured to determine the plugging effect of concrete specimens with or without added Al\textsubscript{2}O\textsubscript{3}.

The average sonic time values of cracks with various widths were measured via the crosshole sonic logging method, as shown in Fig. 7. The sonic time values of the unrepaired specimens were significantly higher than those repaired and non-cracked samples. The sonic time values of all unrepaired specimens with various crack widths was between 60 ~ 65 μs and they were larger with increasing crack width.

The sonic time values of concrete specimens without cracks were the lowest, which remained at about 32 μs. The sonic time values of the repaired specimens of various widths were reduced after repairing. Compared with specimens without added Al\textsubscript{2}O\textsubscript{3}, the sonic time values of those with added Al\textsubscript{2}O\textsubscript{3} was significantly reduced. There are two reasons for such phenomena. One was that adding Al\textsubscript{2}O\textsubscript{3} would decrease sonic time values, which was demonstrated by the differences in sonic time values between unrepaired specimens and those unrepaired but with added Al\textsubscript{2}O\textsubscript{3}. The other reason was that Al\textsubscript{2}O\textsubscript{3} allowed more carbonate precipitation to remain in the cracks, which significantly reduced sonic time values. This reason also explained why the difference in sonic time values between unrepaired specimens with added Al\textsubscript{2}O\textsubscript{3} and repaired samples with added Al\textsubscript{2}O\textsubscript{3} was larger.

It is worth noting that the decreasing range of sonic time values with added Al\textsubscript{2}O\textsubscript{3} was larger with decreasing crack width, as smaller cracks were more effectively plugged. With a smaller crack width (1 mm), the bottom of the crack was not repaired completely and its sonic time value was about 40 μs. The middle and upper parts of the cracks were blocked earlier and almost completely filled, so their sonic time values decreased to 36 μs, close to those of specimens without cracks. However, for larger cracks (width 2 mm), more bacteria stayed at the bottom of crack, so the upper part of the crack was not well repaired, and its sonic time value was relatively high at about 50 μs.

As for specimens without added Al\textsubscript{2}O\textsubscript{3}, less calcium carbonate was produced due to insufficient repair time, resulting in a smaller level of repair. Moreover, the larger the crack width, the worse the repair effect, and the larger the sonic time value.

The conclusions were consistent with the previous research obtained from analyzing pH and utilization rates of urea in leachate.

### 3.5 Unconfined compressive strength tests

The bioremediation of concrete specimens based on MICP was initiated by Ramachandran \textit{et al.} (2001). To demonstrate the strength of MICP based repair of concrete, unconfined compression tests were carried out and the strength data are shown in Table 2. As can be seen from Table 2, the strength of specimens with no cracks was the highest, reaching 61.86 MPa. Concrete specimens containing cracks had significantly decreased strength. The strength of specimens with cracks of 1.0 mm was about 33.54 MPa and the strength loss was 45.86%. The strength of specimens with cracks of 1.5 mm was about 31.71 MPa and the strength loss was 48.74%, while the strength of specimens with cracks of 2.0 mm was about 30.05 MPa and the strength loss was 51.49%. Therefore, the loss of strength increased with increasing crack width.

Concrete specimens that had their cracks cured using the bio-remediation method recovered their strength to a certain degree. Moreover, cracks with a smaller width
generally recovered a greater degree of strength. For those without added Al(OH)₃ and a crack width of 1.0 mm or 1.5 mm, the strength of specimens increased by 7.32% and 5.79% (38.07 MPa and 35.29 MPa) and reaching 61.54% and 57.05% of those without cracks, respectively. With a larger crack width of 2.0 mm, their strength increased by 6.08% (33.81 MPa) and reaching 54.66% of those without cracks. The bio-remediation based improvement was much smaller than in previous studies. The compressive strength of the remediated concrete increased by 12% in 7 days; however, only by 3% in 28 days (Lv and Chen 2012). Wang et al. (2012) evaluated bio-remediation efficiency by means of strength regain (by 60%) in mortar prisms and a decrease in water permeability (10¹⁰ to 10¹¹ m/s coefficient) in concrete cylinders. In these studies the crack width was larger, but the curing time was shorter.

With added Al(OH)₃, the unconfined compressive strengths of the specimens were significantly higher than those without added Al(OH)₃, regardless of crack width. The ultimate strength of the specimen with a crack width of 2.0 mm after repairing was still lower than those with a crack width of 1.0 mm, as shown in Table 2.

With a crack width of 1 mm, the strength of the repaired specimen with added Al(OH)₃ was 50.12 MPa, which increased by 58.55%, reaching 81.02% of those without cracks. The strength increased by 12.05 MPa compared with those with the same crack width but without added Al(OH)₃, which was caused by the dual function of filling of Al(OH)₃ and more calcium carbonate. With a crack width of 2.0 mm, the strength of the repaired specimen with added Al(OH)₃ was 44.33 MPa and the repair effect was 44.89%, reaching 75.84% of those without cracks. Adding Al(OH)₃ improved the strength by 10.52 MPa, therefore, the effect of adding Al(OH)₃ decreased with increasing crack width.

Therefore, after MICP repairing, the strength of all specimens with different crack widths increased. With a smaller crack width, the strength increased more significantly and adding Al(OH)₃ further improved the repair of these cracks.

4. Conclusions

Bio-remediation was used to repair various cracks in concrete specimens and the method of adding Al(OH)₃ was proposed to study its effect on improving strength. The effect of adding Al(OH)₃ on the pH of the medium, urease activity and productive rates for calcium carbonate were studied. The repairing effect was evaluated via the pH and urea utilization rate of the leachate, sonic time values and unconfined compressive strength. The results provide an important reference for bio-remediation in practical engineering applications. Specific conclusions are outlined as follows:

1. Adding Al(OH)₃ reduced the initial pH value of the medium to quickly obtain a weak alkaline environment. Moreover, adding Al(OH)₃ significantly improved bacterial urease activity and the larger the amount of alumina, the higher the urease activity.

2. Adding Al(OH)₃ reduced the pH in the process of bio-remediation, accelerating the MICP reaction and producing more calcium carbonate precipitation. Increasing the amount of added Al(OH)₃ reduced the pH, which was more suitable for the MICP reaction.

3. Adding Al(OH)₃ in cracks allowed the initial pH to stay below 10 so as to provide a suitable environment for the growth of bacteria, increasing significantly the urea utilization rate to produce more carbonate precipitation. The method had a positive influence on the MICP reaction.

4. Compared with specimens without added Al(OH)₃, those with added Al(OH)₃ were repaired better and their sonic time values were significantly reduced. Moreover, the decreasing range of sonic time values of specimens with added Al(OH)₃ was larger.

5. After bio-remediation, the strengths of all specimens with various crack widths increased, and the smaller the crack width, the more significant the strength increase. With added Al(OH)₃, the strengths of the specimens were significantly higher than those without added Al(OH)₃.

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References

Achal, V. and Mukherjee, A., (2015). “A review of microbial precipitation for sustainable construction.” Construction and Building Materials, 93, 1224-1235.

Achal, V., Mukherjee, A., Kumari, D. and Zhang, Q., (2015). “Biominalization for sustainable construction—A review of processes and applications.” Earth-science reviews, 148, 1-17.

Alazhari, M., Sharma, T., Heath, A., Cooper, R. and Paine, K., (2018). “Application of expanded perlite encapsulated bacteria and growth media for self-healing concrete.” Construction and Building Materials, 160, 610-619.

Araújo, M., Vlierberghe, S. V. and Feiteira, J., (2016). “Cross-linkable polyethers as healing/sealing agents for self-healing of cementitious materials.” Materials and Design, 98, 215-222.

Bang, S. S., Lippert, J. J., Yerra, U., Mulukutla, S. and Ramarkrishnan, V., (2010). “Microbial calcite, a bio-based smart nanomaterial in concrete remediation.” International Journal of Smart and Nano Materials, 1, 28-39.

Blaiszik, B. J., Kramer, S. L., Olugebefola, S. C., Moore, J. S., Sottos, N. R. and White, S. R., (2010). “Self-healing polymers and composites.” Annual Review of Materials Research, 40, 179-211.

Campbell, T., Kalia, R. K., Nakano, A., Vashishta, P., Ogata, S., and Rodgers, S., (1999). “Dynamics of oxidation of aluminum nanoclusters using variable charge molecular-dynamics simulations on parallel computers.” Physical Review Letters, 82(24), 4866-4869.

Caruso, M. M., Blaiszik, B. J., White, S. R., Sottos, N. R. and Moore, J. S., (2008). “Full recovery of fracture toughness using a nontoxic solvent-based self-healing system.” Advanced Functional Materials, 18(13), 1898-1904.

Choi, A. L., Sun, G., Ying, Z. and Philippe, G., (2012). “Developmental fluoride neurotoxicity: a systematic review and meta-analysis.” Environmental Health Perspectives, 120(10), 1362-1368.

Cölfen, H. and Antonietti, M., (1998). “Crystal design of calcium carbonate microparticles using double-hydrophilic block copolymers.” Langmuir, 14(3), 582-589.

Cui, D. and Ping, G., (2011). “Rehabilitation of concrete beam by using martensitic shape memory alloy strands.” Advanced Materials Research. 243-249, 5527-5530.

De Muynck, W., Debrouwer, D., De Belie, N. and Verstraete, W., (2008). “Bacterial carbonate precipitation improves the durability of cementitious materials.” Cement and concrete Research, 38(7), 1005-1014.

De Muynck, W., Verbeken, K., De Belie, N. and Verstraete, W., (2013). “Influence of temperature on the effectiveness of a biogenic carbonate surface treatment for limestone conservation.” Applied Microbiology and Biotechnology, 97, 1335-47.

De Rooij, M., Van Tittelboom, K., De Belie, N. and Schlangen, E., (Eds.) (2013). “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.” RILEM State of the Art Reports, Springer Science & Business Media.

Edvardsen, C., (1999). “Water permeability and autogenous healing of cracks in concrete.” ACI Mater. J., 96(4), 448-454.

Feiteira, J., Gruyaert, E. and Belie, N. D., (2016a). “Self-healing of moving cracks in concrete by means of encapsulated polymer precursors.” Construction and Building Materials, 102, 671-678.

Ferrara, L., Krelani, V. and Moretti, F., (2016b). “On the use of crystalline admixtures in cement based construction materials: from porosity reducers to promoters of self healing.” Smart Materials & Structures, 25(8), 084002.

Jonkers, H. M., Thijsse, A., Muyzer, G., Cipuroglu, O. and Schlangen, E., (2010). “Application of bacteria as self-healing agent for the development of sustainable concrete.” Ecological Engineering, 36(2), 230-235.

Hammes, F., Boon, N., de Villiers, J., Verstraete, W. and Siciliano, S. D., (2003a). “Strain-specific ureolytic microbial calcium carbonate precipitation.” Applied and Environmental Microbiology, 69, 4901-4909.

Hearn, N., (1998). “Self-sealing, autogenous healing and continued hydration: What is the difference?” Mater. Struct., 31, 563-567.

Hillewaere, X. K., Teixeira, R. F., Nguyen, L.-T. T., José A., Ramos, J. A., Rahier, H. and Du Prez, F. E., (2014). “Autonomous self-healing of epoxy thermosts with thiol-isocyanate chemistry.” Advanced Functional Materials, 24(35), 5575-5583.

Huang, H., Ye, G. and Damidot, D., (2013). “Characterization and quantification of self-healing behaviors of microcracks due to further hydration in cement paste.” Cement and Concrete Research, 52, 71-81.

Ivanov, V. M., Figurovskaya, V. N., Barbalat, Y. A. and Ershova, N. I., (2005). “Chromaticity characteristics of NH2Hg2I3 and I2: Molecular iodine as a test form alternative to Nessler’s reagent.” J. Anal. Chem., 60(7), 707-710.

Ivanov, V. and Chu, J., (2008). “Applications of microorganisms to geotechnical engineering for biooclogging and biocementation of soil in situ.” Reviews in Environmental Science and Biotechnology, 7(2), 139-153.

Jauberthie, R. and Rendell, F., (2003). “Physicochemical study of the alteration surface of concrete exposed to ammonium salts.” Cement and Concrete Research, 33(1), 85-91.
Kessler, M. R., Sottos, N. R. and White, S. R., (2003). “Self-healing structural composite materials.” Composites Part A: applied science and manufacturing, 34(8), 743-753.

Khaliq, W. and Ehsan, M. B., (2016). “Crack healing in concrete using various bio influenced self-healing techniques.” Construction and Building Materials, 102, 349-357.

Khan, M. N. H. and Amarakoon, G. G. N. N., (2015). “Coral sand solidification test based on microbially induced carbonate precipitation using ureolytic bacteria.” Materials Transactions, 56(10), 1725-1732.

Lee, H. X. D., Wong, H. S. and Buenfeld, N. R., (2015). “Characterization of sustainable bio-based self-healing agents on cementitious materials by the combination of superabsorbent polymers.” Cement and Concrete Research, 79, 194-208.

Li, W., Liu, L., Chen, W., Yu, L., Li, W. and Yu, H., (2010). “Calcium carbonate precipitation and crystal morphology induced by microbial carbonic anhydrase and other biological factors.” Process Biochemistry, 45, 1017-1021.

Lors, C., Ducasse-Lapeyrusse, J., Gagné, R. and Damidot, D., (2017). “Microbiologically induced calcium carbonate precipitation to repair microcracks remaining after autogenous healing of mortars.” Construction and Building Materials, 141, 461-469.

Luhr, S. and Gourav, S., (2015). “A review paper on self healing concrete.” Journal of Civil Engineering Research, 5(3), 53-58.

Luo, M. and Qian, C., (2016). “Influences of bacteria-based self-healing agents on cementitious materials hydration kinetics and compressive strength.” Construction and Building Materials, 121, 659-663.

Luo, M., Qian, C. X. and Li, R. Y., (2015). “Factors affecting crack repairing capacity of bacteria-based self-healing concrete.” Construction and Building Materials, 87, 1-7.

Lv, Z. and Chen, H., (2012). “Modeling of self-healing efficiency for cracks due to unhydrated cement nuclei in hardened cement paste.” Procedia Engineering, 27, 281-290.

Martinez, B. C., DeJong, J. T., Ginn, T. R. and Montoya, B. M., (2013). “Experimental optimization of microbial-induced carbonate precipitation for soil improvement.” J. Geotech. Geoenviron. Eng., 139(4), 587-598.

Pacheco-Torgal, F. and Labrincha, J. A., (2013). “Biotech cementitious materials: some aspects of an innovative approach for concrete with enhanced durability.” Construction and Building Materials, 40(7), 1136-1141.

Pang, B., Zhou, Z., Hou, P., Du, P., Zhang, L. and Xu, H., (2016). “Autogenous and engineered healing mechanisms of carbonated steel slag aggregate in concrete.” Construction and Building Materials, 107(6), 191-202.

Pu, Q., Jiang, L., Xu, J., Chu, H., Xu, Y. and Zhang, Y., (2012). “Evolution of pH and chemical composition of pore solution in carbonated concrete.” Construction and Building Materials, 28(1), 519-524.

Qabany, A. A., Soga, K. and Santamarina, C., (2012). “Factors affecting efficiency of microbially induced calcite precipitation.” Journal of Geotechnical and Geoenvironmental Engineering, 138(8), 992-1001.

Ramachandran, S. K., Ramakrishnan, V. and Bang, S. S., (2001). “Remediation of concrete using microorganisms.” ACI Mater. J, 98(1), 3-9.

Ranaivomanana, H., Verdier, J., Sellier, A. and Bourbon, X., (2013). “Sealing process induced by carbonation of localized cracks in cementitious materials.” Cement and Concrete Composites, 37(1), 37-46.

Rodriguez-Navarro, C., Rodriguez-Gallego, M., Chekrour, K. B. and Gonzalez-Munoz, M. T., (2003). “Conservation of ornamental stone by Myxococcus xanthus-induced carbonate biomineralization.” Applied and Environmental Microbiology, 69, 2182-2193.

Roig-Flores, M., Pirritano, F., Serna, P. and Ferrara, L., (2016). “Effect of crystalline admixtures on the self-healing capability of early-age concrete studied by means of permeability and crack closing tests.” Construction and Building Materials, 114, 447-457.

Schlangen, E. and Sangadji, S., (2013). “Addressing infrastructure durability and sustainability by self healing mechanisms - recent advances in self healing concrete and asphalt.” Procedia Engineering, 54, 39-57.

Shin, M. and Andrawes, B., (2011). “Emergency repair of severely damaged reinforced concrete columns using active confinement with shape memory alloys.” Smart Materials and Structures, 20(6), 065018.

Sierra-Beltran, M. G., Jonkers, H. M. and Schlangen, E., (2014). “Characterization of sustainable bio-based mortar for concrete repair.” Construction and Building Materials, 67, 344-352.

Snoeck, D., Van Tittelboom, K., Steuperert, S., Dubruel, P. and De Belle, N., (2014), “Self-healing cementitious materials by the combination of microfibers and superabsorbent polymers.” J. Intell. Mater. Sys. Struct., 25(1), 13-24.

Stocks-Fisher, S., Galinat, J. K. and Bang, S. S., (1999). “Microbiological precipitation of CaCO3.” Soil Biol. Biochem., 31(11), 1563-1571.

Stuckrath, C., Serpell, R., Valenzuela, L. M. and Lopez, M., (2014). “Quantification of chemical and biological calcium carbonate precipitation: performance of self-healing in reinforced mortar containing chemical admixtures.” Cement and Concrete Composites, 50, 10-15.

Sun, X., Miao, L. and Wang, C., (2018). “Improvement of microbial-induced calcium carbonate precipitation technology for sand solidification.” Journal of Materials in Civil Engineering, 30(11), 04018301.

Sun, X., Miao, L. and Wang, C., (2018b). “Experimental study on calcium carbonate precipitates induced by
bacillus megaterium.” In: W. Wu and H. S. Yu, Eds. Proceedings of China-Europe Conference on Geotechnical Engineering, Springer Series in Geomechanics and Geoengineering, Springer, Cham, 834-837.

Talaiekhoozan, A., Keyvanfar, A., Shafaghat, A., Andalib, R., Abd Majid, M. Z., Fulazzaky, M. A., Zin, R. M., Lee, C. T., Hussin, M. W., Hamzah, N., Marwar, N. F. and Haidar, H. I. (2014). “A review of self-healing concrete research development.” Journal of Environmental Treatment Techniques, 2(1), 1-11.

Tziviloglou, E., Wiktor, V., Jonkers, H. M. and Schlangen, E. (2016). “Bacteria-based self-healing concrete to increase liquid tightness of cracks.” Construction and Building Materials, 122, 118-125.

Van Tittelboom, K., De Belie, N., De Muynck, W., Verstraete, W. (2010). “Use of bacteria to repair cracks in concrete.” Cement and Concrete Research, 40(1), 157-166.

Wang, J., Tittelboom, K. V., Belie, N. D. and Verstraete, W. (2012). “Use of silica gel or polyurethane immobilized bacteria for self-healing concrete.” Construction and Building Materials, 26(1), 532-540.

Wang, J. Y., De Belie, N. and Verstraete, W. (2012). “Diatomaceous earth as a protective vehicle for bacteria applied for self-healing concrete.” Journal of industrial microbiology and biotechnology, 39(4), 567-577.

Wang, J. Y., Soens, H., Verstraete, W. and De Belie, N., (2014). “Self-healing concrete by use of microencapsulated bacterial spores.” Cement and Concrete Research, 56(2), 139-152.

Wang, J. Y., Belie, N. D. and Verstraete, W. (2012). “Diatomaceous earth as a protective vehicle for bacteria applied for self-healing concrete.” J. Ind. Microbiol. Biotechnol., 39(4), 567-577.

Whiffin, V. S. (2004). “Microbial CaCO3 precipitation for the production of bioceement.” Thesis (PhD). Murdoch University, Perth, Australia.

White, S. R., Sottos, N. R., Geubelle, P. H., Moore, J. S., Kessler, M. R., Sriram, S. R., Brown E. N. and Viswanathan, S., (2001). “Autonomic healing of polymer composites.” Nature, 409(6822), 794.

Wiktor, V., and Jonkers, H. M., (2011). “Quantification of crack-healing in novel bacteria-based self-healing concrete.” Cement and Concrete Composites, 33(7), 763-770.

Wiktor, V. and Jonkers, H. M., (2015). “Field performance of bacteria-based repair system: pilot study in a parking garage.” Case Studies in Construction Materials, 2, 11-17.

Wu, M., Johannesson, B. and Geiker, M., (2012). “A review: self-healing in cementitious materials and engineered cementitious composite as a self-healing material.” Construction and Building Materials, 28(1), 571-583.

Sun, X. and Miao, L., (2018). “The Comparison of microbiologically-induced calcium carbonate precipitation and magnesium carbonate precipitation.” In: Proceedings of the 8th International Congress on Environmental Geotechnics, Singapore, Springer, 3, 302-308.

Yang, Z. and Cheng, X., (2013). “A performance study of high-strength microbial mortar produced by low pressure grouting for the reinforcement of deteriorated masonry structures.” Construction and Building Materials, 41(2), 505-515.

Zhan, Q., Qian, C. and Yi, H., (2016). “Microbial-induced mineralization and cementation of fugitive dust and engineering application.” Construction and Building Materials, 121, 437-444.

Zhang, Y., Guo, H. X., and Cheng, X. H., (2015). “Role of calcium sources in the strength and microstructure of microbial mortar.” Construction and Building Materials, 77, 160-167.

Zhu, T. and Dittrich, M., (2016). “Carbonate precipitation through microbial activities in natural environment, and their potential in biotechnology: a review.” Frontiers in Bioengineering and Biotechnology, 4(4), 4.