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Concrete crack rehabilitation using biological enzyme

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Abstract. Concrete is a material popularly used in construction. Due to the load-bearing and external environmental factors during utilization or manufacturing, its surface is prone to flaws, such as crack and leak. To repair these superficial defects and ultimately and avoid the deterioration of the concrete's durability, numerous concrete surface protective coatings and crack repair products have been developed. Currently, studies are endeavoring to exploit the mineralization property of microbial strains for repairing concrete cracks be the repairing material for crack rehabilitation. This research aims to use bacteria, specifically B. *pasteurii*, in crack rehabilitation to enhance the flexural and compression strength of the repaired concrete.

Serial tests at various bacterial concentrations and the same Urea-$CaCl_2$ medium concentration of 70% for crack rehabilitation were executed. The results prove that the higher the concentration of the bacterial broth, the greater the amount of calcium carbonate precipitate was induced, while using B. *pasteurii* broth was for crack rehabilitation. The flexural and compression strengths of the repaired concrete test samples were the greatest at 100% bacterial concentration. Compared to the control group (bacterial concentration of 0%), the flexural strength had increased by 32.58% for 1-mm crack samples and 51.01% for 2-mm crack samples, and the compression strength had increased by 28.58% and 23.85%, respectively. From the SEM and XRD test results, a greater quantity of rectangular and polygonal crystals was also found in samples with high bacterial concentrations. These tests all confirm that using bacteria in crack rehabilitation can increase the flexural and compression strength of the repaired concrete.

Keywords: concrete crack; biological rehabilitation; enzyme; flexural strength; compression strength

1. Introduction

Currently, concrete is the most popularly used material in construction. However, because of the load-bearing and external environmental factors during utilization or manufacturing, its surface is prone to flaws, such as loosening, flaking, and even microscopic cracking within the internal structure of the material. If these defects are not repaired promptly, water and corrosive substances infiltrate the material through these superficial defects and ultimately accelerate the deterioration of the concrete's durability (Yang and Su 2006, Yang and Su 2008). When exposed to high temperature, concrete is apt to crack due to its changes in chemical composition, physical structure and water content (Tang 2010). Especially, crack rehabilitation is urgently needed for sewer pipes made of concrete after inspection (Yang and Su 2009, Su *et al.* 2011, Yang *et al.* 2011a, Yang *et al.* 2011b). Usually, computer modeling using finite element with an embedded crack can be used to model tensile fracture in concrete solids and crack growth (Dujc *et al.* 2010). When cracks occur, various concrete surface protective coatings and crack repair products, such as epoxy resins, cementitious capillary crystalline materials, polymer mortars, and polymergrout materials, can be chosen in the market. Studies were endeavoring to exploit the mineralization property of microbial strains for cementing sand columns, repairing concrete cracks, protecting concrete surfaces, and repairing ancient architecture (Nemati and Voordouw 2003, Stocks-Fischer *et al.* 1991, Rodriguez *et al.* 2003, Dick *et al.* 2006). Through thermogravimetric analysis, bacteria protected in silica gel were proven able to precipitate $CaCO_3$ crystals inside cracks and fill cracks completely (Van Tittelboom *et al.* 2010). Recently, the mortar specimens with hydrogel-encapsulated spores also showed a distinct self-healing superiority through thermogravimetric analysis (Wang *et al.* 2014a).

Specific microbe types react while contacting positively charged ions in a soluble substance. Positive ions are attracted by the negatively charged ions on the ends of microbes and, consequently, adhere to the microbe. Then, a chemical reaction occurs between the charged ions and the carbonate ions because of the microbial deterioration of the substance. This causes the precipitation of carbonates around the peripheral of the microbe (De Muynck *et al.* 2008). This type of biological carbonate material has cementitious properties and can be used to fill pores or reinforce the consolidation of surrounding substances. For example, the crack-healing potential of a two-component bio-chemical self-healing agent embedded in porous expanded clay particles was quantified as crack-healing of up to 0.46 mm-wide cracks in bacterial concrete compared to only up to 0.18 mm-wide cracks in control specimens after 100 days submersion in water (Wiktor and Jonkers, 2011). Application of microcapsules to encapsulate bacterial spores for self-healing concrete indicated that the healing

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Fig. 1 Superficial cracks on the test samples with 1-mm width (lower) and 2-mm width (upper)

ratio in the specimens with bio-microcapsules was higher (48%-80%) than in those without bacteria (18%-50%) (Wang *et al.* 2014b). Recently, Ureolytic activity, calcium carbonate precipitation capability, and the effects in concrete were evaluated at production scales of 5 L and 50 L to provide an inexpensive bio-agent of self-healing concrete (Da Silva *et al.* 2015).

B. pasteurii is a gram-positive aerobic bacteria strain commonly present in soil, which can produce large quantities of cellular urease for reducing urea into ammonium ions and carbon dioxide. *B. pasteurii* can then react with calcium chloride to induce calcite precipitation, facilitating the bonding of sandy soil and transforming quicksand into sandstone. Urease catalyzes the hydrolysis of urea to produce carbon dioxide, ammonium ion, and hydrogen ions; the reaction formula is as Eq. (1)

$$NH_2(CO)NH_2 + 3H_2O \rightarrow 2NH_4 + 2OH^- + CO_2 \quad (1)$$

By releasing OH^- so to increase pH, CO_2 turns into CO_3^{2-} which bonds with C_a^{2-} in the surrounding to be C_aCO_3 (Bang *et al.* 2001, Bachmeier *et al.* 2002). Calcite precipitation induced by *B. pasteurii* was studied for concrete remediation and showed a significant increase in compressive strength of the portland cement mortar cubes containing lower concentrations of live cells (Ramachandran *et al.* 2001). This research aims to use bacteria, specifically *B. pasteurii*, in crack rehabilitation so to enhance the flexural strength and compression strength of the repaired concrete.

2. Materials and methodology

2.1 Experimental materials

(1) *B. pasteurii*: The strain was purchased from the Bioresource Collection and Research Center of Food Industry Research and Development Institute, Taiwan. The strain code was BCRC11596. We selected an absorbance of O.D. 600=1 for the 100% bacteria concentration sample. This study used five bacterial concentrations, namely, 0%, 25%, 50%, 75%, and 100%.

(2) Urea-$CaCl_2$ medium: In 1L of deionized water, we added urea (20 g), $CaCl_2$ (2.8 g), and yeast extract to create the 100% concentration sample. The concentration of 70% was used.

Table 1 Concrete mixed proportion (kg/m^3)

W/B	Cement	Slag	Fly Ash	Water	Aggregate		Slump (mm)
					Fine	Coarse	
0.7	174	77	44	203	987	774	100

Notation:
• Fine aggregate: Fineness modulus 2.60, specific weight (SSD) 2.65 and absorption (SSD) 1.20%
• Coarse aggregate: Specific weight (SSD) 2.63 and absorption (SSD) 1.00%

Table 2 Mixed proportion of repairing material (kg/m^3)

Sample ID	Sludge	Sands	B.P.	Phosphate buffer	Urea-$CaCl_2$
A-100-70	750	750	225.00	0	225.00
A-075-70	750	750	168.75	56.25	225.00
A-050-70	750	750	112.50	112.50	225.00
A-025-70	750	750	56.25	168.75	225.00
A-000-70	750	750	0	225.00	225.00

Notation:
• 100, 075, 050, 025 and 000 represent the concentration of bacteria
• 70 represents the concentration of Urea-$CaCl_2$ medium

(3) Urea medium: In 1 L of de-ionized water, we added 20 g urea and yeast extract.

(4) Sludge: Raw material (sludge) was obtained from the sedimentation tank located at the downstream of the Shihmen Reservoir in northern Taiwan. The material belongs to the CL soil category, has moderate particle diameters of D_{50}<0.01 mm, and the primary constituent is SiO_2 (Chen *et al.* 2012).

(5) Fine aggregate: Natural river sand from Taiwan was used. The fineness modulus (FM) was 2.76; the saturated surface dry bulk specific gravity was 2.64; and the water absorption rate was 0.9%.

2.2 Experiment design

With a mixed proportion as listed in Table 1 and slump of 100 mm, liquid concrete were poured into 100 mm×100 mm×360 mm and 75 mm×75 mm×75 mm vessels as specimens. Cracks of 1 mm and 2 mm with 100 mm length and 30 mm depth were manually made on the surface of two size specimens, respectively, as test samples (Fig. 1). The mixture of microbes, urea medium, and urea-$CaCl_2$ medium was added to a sludge and fine aggregate with a weight ratio of 0.6:1:1 as listed in Table 2, and fully mixed to be the repairing material for crack rehabilitation. Crack rehabilitation was conducted by injected the mixture into the test samples after 90 days curing in saturated lime solution. Several tests were conducted on the repaired samples after 3, 7, 14, and 28 days. Four kinds of tests are addressed as follows.

(1) Flexural test: The ASTM C78 method was used to conduct a flexural strength test.

(2) Compression test: The ASTM C109 method was used to conduct a compression strength test.

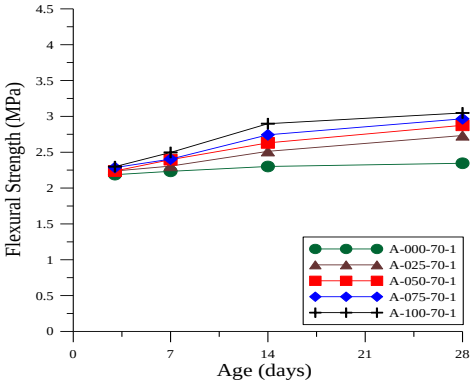

Fig. 2 Flexural test on repaired samples with 1-mm crack

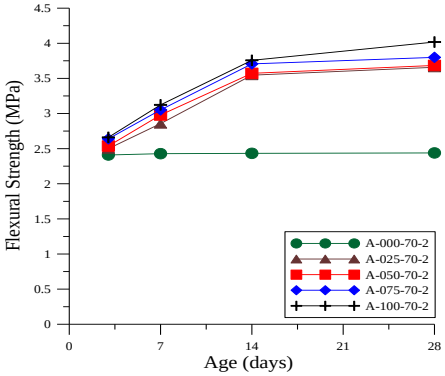

Fig. 3 Flexural test on repaired samples with 2-mm crack

(3) XRD test: A powder X-ray diffraction machine, PANalytical X'Pert Pro MRD, was used to analyze the test sample's internal crystalline structure and observe the crystal formation condition of its calcium carbonates.

(4) SEM test: The structural composition of the test sample was captured by TM-1000 to analyze calcium carbonate crystal formation.

3. Tests and result analysis

3.1 Flexural test

The influence of bacteria in the flexural strength of test samples under Urea-$CaCl_2$ medium concentration of 70% was observed in flexural test. Figs. 2 and 3 show the experimental result of crack rehabilitation on the test samples with 1-mm crack and 2-mm crack, respectively. The enhancement of flexural strength is significant on the test samples with bacteria concentration, especially with 100% concentration bacteria. This may be caused by more $CaCO_3$ converted by CO_3^{2-} due to sufficient enzyme in high bacteria concentrations. The flexural strength of the repaired concrete at day 28 ranged from 2.19 MPa to 3.05 MPa for 1-mm crack test and from 2.41 MPa to 4.02 MPa for 2-mm crack test. For comparison, the flexural strength of the group with 0% bacterial concentration remained consistent (between 2.19 MPa and 2.35 MPa for 1-mm crack test and 2.41 MPa and 2.44 MPa for 2-mm crack test) during the test period. The test samples with 100% bacterial concentration had significant enhancement with the test

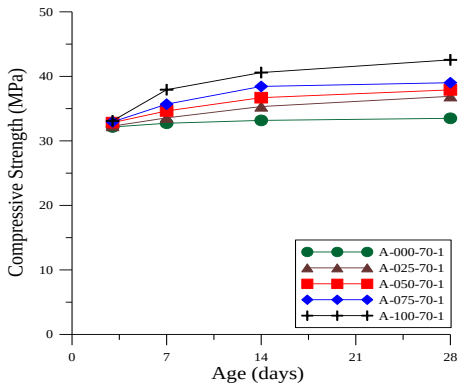

Fig. 4 Compression test on repaired samples with 1-mm crack

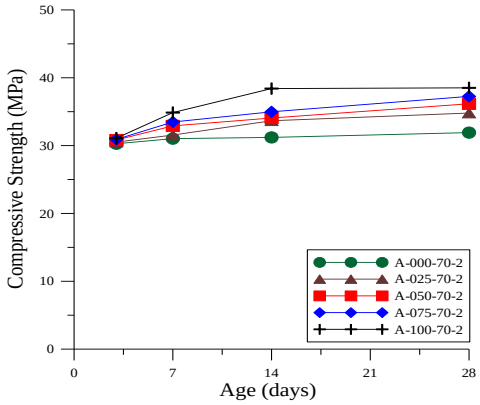

Fig. 5 Compression test on repaired samples with 2-mm crack

time going by. An increase of 32.58% and 51.01% in flexural strength was observed by comparing day-28 test sample (2.30 MPa and 2.66 MPa) with day-3 test sample (3.05 MPa and 4.02 MPa) for 1-mm crack test and 2-mm crack test, respectively. Therefore, we concluded that bacteria provided a superior rehabilitation effect in flexural strength improvement.

With the Urea-$CaCl_2$ medium concentration of 70%, day-3 test samples showed no difference in flexural strength than the control group (i.e., the group with 0% bacterial concentration). For longer age test samples, flexural strength increased with age. Furthermore, the 100% concentration of bacteria had the highest flexural strength in all age test samples, whereas the group with 0% bacterial concentration had the least flexural strength. This result indicates that the bacterial concentration increases the flexural strength of the test samples.

3.2 Compression test

Figs. 4 and 5 show the compression test results of crack rehabilitation on the test samples with 1-mm crack and 2-mm crack, respectively. The flexural strength of the repaired concrete at day 28 ranged from 32.16 MPa to 42.56 MPa and 30.28 MPa to 38.51 MPa for 1-mm crack test and 2-mm crack test, respectively. For comparison, the compression strength of the group with 0% bacterial concentration remained consistent during the test period.

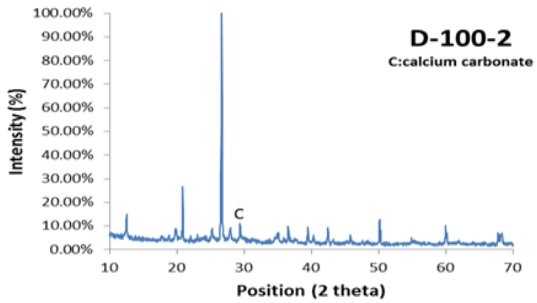

Fig. 6 Day-28 XRD test of the microbe-repaired samples with 100% bacteria and 70% Urea-$CaCl_2$ medium concentration

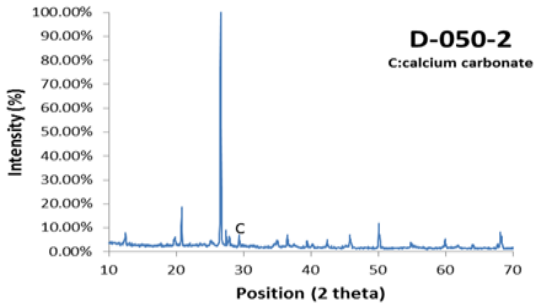

Fig. 7 Day-28 XRD test of the microbe-repaired samples with 50% bacteria and 70% Urea-$CaCl_2$ medium concentration

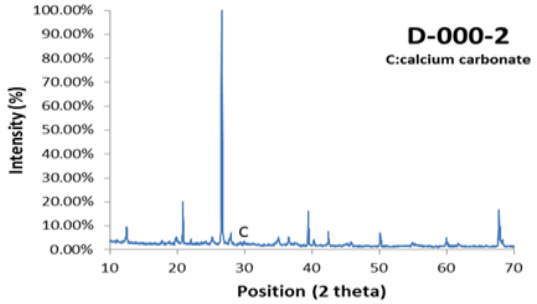

Fig. 8 Day-28 XRD test of the microbe-repaired samples with no bacteria and 70% Urea-$CaCl_2$ medium concentration

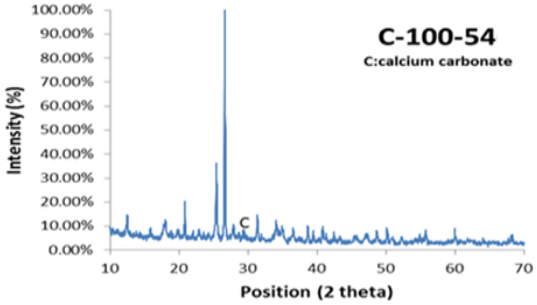

Fig. 9 Day-7 XRD test of the microbe-repaired samples with 100% bacteria and 70% Urea-$CaCl_2$ medium concentration

The test samples with 100% bacterial concentration had significant enhancement with the test time going by. An increase of 28.58% and 23.85% in compression strength was observed by comparing day-28 test sample (42.56 MPa and 38.51 MPa) with day-3 test sample (33.10 MPa and 31.10 MPa) for 1-mm crack test and 2-mm crack test, respectively. Therefore, we concluded that bacteria provided a superior rehabilitation effect in compression strength improvement.

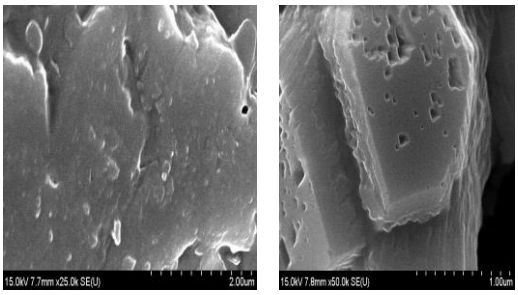

Fig. 10 Day-28 SEM test of the microbe-repaired samples with no bacteria and 70% Urea-$CaCl_2$ medium concentration

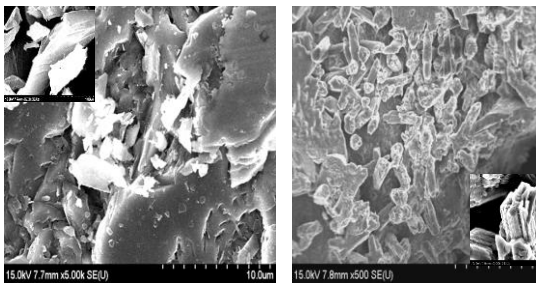

Fig. 11 Day-28 SEM test of the microbe-repaired samples with 100% bacteria and 70% Urea-$CaCl_2$ medium concentration

3.3 XRD test and SEM test

Figs. 6-9 show the XRD test results of various bacterial concentrations at a Urea-$CaCl_2$ medium concentration of 70%. The results indicate that groups containing bacteria all possessed calcium carbonate crystals. However, possibly because of the minute quantities, the X-ray diffraction intensity was not significantly affected. Nonetheless, the results in Figs. 6 and 9 revealed that the calcium carbonate crystal peak values at day 28 were more distinct than at day 7. This shows that the calcium carbonate crystal quantities in the test sample at that age were higher than at other ages. However, although the Urea-$CaCl_2$ medium was added to the control group during the mixing process, calcium carbonate crystals were not observed. This may be caused by the lack of bacteria in the sample. Although urea does degrade spontaneously, the deterioration speed is not ideal. The surrounding pH values do not increase at a sufficiently rapid rate; thus, CO_2 lack adequate time to convert into CO_3^{2-} before dissipating. This results in limited carbonates, which are then unable to react with free Ca^{2+} to create calcium carbonate precipitates.

Figs. 10 and 11 are SEM photographs of the samples for the control group at 100% bacterial concentration. In the experimental group, various rectangular and polygonal

crystals were observed in the photographs. By contrast, the microbe-absent repaired concrete does not exhibit rectangular and polygonal crystal particles. These results demonstrated that bacteria can induce calcium carbonate precipitation to complete crack rehabilitation and improve the repaired concrete strength for the microbe-repaired test samples.

4. Conclusions

Serial tests at various bacterial concentrations and the same Urea-$CaCl_2$ medium concentration of 70% for crack rehabilitation were executed. Two major points were concluded for concrete crack rehabilitation using bacteria as follows:

• The higher the concentration of the bacterial broth was, the greater the amount of calcium carbonate precipitate was induced, while using *B. pasteurii* broth for crack rehabilitation. At a 70% Urea-$CaCl_2$ medium concentration, the flexural and compression strengths of the repaired concrete test samples were the greatest at 100% bacterial concentration. Compared to the control group (bacterial concentration of 0%), the flexural strength had increased by 32.58% for 1-mm crack test and 51.01% for 2-mm crack test, and the compression strength had increased by 28.58% and 23.85%, respectively. This proves that using bacteria in crack rehabilitation can increase the flexural and compression strength of the repaired concrete.

• From the SEM and XRD test results, we found that the lens captured a greater quantity of rectangular and polygonal crystals in samples with higher bacterial concentrations compared to that of the control group. The structural composition of the crystals was also relatively denser. This verified that bacteria can induce the precipitation of calcium carbonate; additionally, higher bacterial concentrations provide better results. By sample constituent analysis using a powder X-ray diffraction machine, we found that the groups containing bacteria exhibited calcium carbonate crystals in all age samples. However, the X-ray diffraction intensity was not affected significantly due to the limited quantity. Nevertheless, we observed that the peak value of calcium carbonate crystals at day 28 was greater than that at other ages.

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