

## Healing of Generated Cracks in Cement Mortar Using MICP

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### Abstract

This research is carried out to investigate pre-existing repair cracks in cement mortar using the microbiologically induced calcium carbonate precipitation (MICP) technology. In the study, 20-cylinder mortar samples (45 mm in diameter and 40 mm in length) were split to have cracked width of various sizes. Out of twenty cracked samples, sixteen samples of average crack width ranging from 0.12 to 1.3 mm were repaired using the MICP method, while four cracked samples, with an average crack width ranging from 0.16 to 1.55 mm were soaked under distilled water. The water permeability and split tensile strength (STS) of these repaired mortars were tested. The amount of CaCO<sub>3</sub> precipitated on the cracked mortar surfaces was evaluated. The results indicated that the MICP repair technique clearly reduced the water permeability of the cracked samples within the range of 73 to 84 %; while water-treated samples were too weak to undergo test. MICP-repaired samples had STS ranging from 29 to 380 kPa after 24 rounds of treatment. A relationship between the STS and percentage amount of CaCO<sub>3</sub> precipitated was observed for samples with an average crack width between 0.29 and 1.1 mm, which indicated that STS increased with percentage increase in CaCO<sub>3</sub> precipitated on the crack surfaces.

**Keywords:** MICP; Split Tensile Strength; Cement Mortar; Permeability.

### 1. Introduction

The generation of cracks in concrete is a natural phenomenon due to earthquakes, weathering or manmade activities which will adversely affect the life and durability of the structures. The measure cause of the crack is due to lower tensile strength and brittle nature of concrete. The harmful pollutants, chemicals, and water penetrate through the cracks which lead to deterioration of concrete. The present methods existing to repair such cracks are the use of chemicals, grout, or surface treatment which could be harmful to the end-users as well as to the environment. Eco-friendly, sustainable and new technique MICP as the new area of interest is a substitute to repair cracks [1]. MICP process depends on ureolytic non-pathogenic bacteria (*Bacillus pasteurii*) to hydrolyze urea in the presence of calcium ion which leads to calcite precipitation. Purified bacterial cells, containing the enzyme in high concentrations, were used to catalyse the hydrolysis of urea and produce ammonium and carbonate ions. Urease enzyme decomposes urea into ammonium (NH<sub>4</sub><sup>+</sup>) and carbonate ions (CO<sub>3</sub><sup>2-</sup>). The combination of this negative carbonate ions and positive Calcium ions (Ca<sup>2+</sup>) available from cementing solution, result in the formation of Calcium Carbonate. The reactions involved are as follows:

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This bio generated  $\text{CaCO}_3$  binds loose particles of matter together, plugs fine pores and cracks. The ultimate effect of this is to increase the engineering properties of concrete and fill the existing cracks, if any. MICP process can be applied for repairing cracks in two ways. First, as pre-treatment where bacteria and cementation solution are mixed with fresh concrete to prevent crack development. This is referred to as autogenous repair or self-healing and another is post-treatment where bacteria and cementation solution are applied in the crack influenced areas of concrete. The use of the MICP method to repair cracks in concrete was studied by several earlier researchers. Substantial and noticeable work was carried by researchers [2-5]. The method of crack healing induced by MICP can be employed in two ways. Alkali-resistant spore-forming bacteria get activated by water and oxygen which infiltrated through cracks and further feed on an available substrate. Subsequently decomposition of a substrate to produce calcium carbonates result in the healing of cracks [4]. Researchers commonly use spore-forming *Bacillus* species micro-organism. *Bacillus pseudofirmus*, *Bacillus sphaericus*, *Bacillus alkalinitrilicus* with calcium lactate were used for investigation. Quantification of crack-healing shows that upto 0.46 mm wide cracks are repaired by bacteria and control specimens after 100 days submersion in water [5].

Another method of self-healing is by mixing of ureolytic microbes which can survive in high alkaline conditions and urease-calcium as nutrients during concrete production. The successful healing of 0.81 mm cracks width after 28 days treatment was reported by using *Bacillus subtilis* with graphite nano-platelets (GNP) and light-weight aggregate (LWA) as carrier compounds [6]. The progress of self-healing by mixing bacteria in fresh concrete is satisfactory. This method is not suitable for the remediation of existing cracks in concrete. Minimum research is available on the repair of existing cracks in concrete. Manual generation of 3.175 mm width of crack at two different depths by saw cut in mortar beam of size 25×25×150 mm was applied during investigation [7]. Remediation was carried by sand and *Bacillus pasteurii*. The compressive strength test on the remediated mortar beams after 28 days of curing in the urea- $\text{CaCl}_2$  solution was conducted. Test results show that cracks were healed and an increase in compressive strength as compared with virgin was noted. An increase in compressive strength by 50% was noticed after MICP treatment given to cement mortar having a crack of 0.3 mm width, 20 mm depth and 50 mm in length. Author Ramachandra concluded that the remediation of shallow cracks in comparison with deeper cracks can be achieved effectively with MICP. The experimentation on repairing crack of dimension 0.3 mm wide × 20 mm deep × 50 mm length in 50 mm cubic mortar by injecting a mixture of *Sporocinapasteurii*, urea- $\text{CaCl}_2$ , and sand showed 50% increase in compressive strength as compared to untreated samples [8]. A similar experiment conducted by (Achal et al., 2013), have used *Bacillus sp.*, to investigate durability properties and remediation of simulated cracks (3 mm in width and 13-27 mm in depth) in 70 mm cubic mortar samples [9]. They found that, more than 50% reduction in porosity, 40% increase in compressive strength and successful healing of the simulated cracks of various depths. Cement mortar specimen of 1:3 cement-sand ratios with different porosity achieved by varying w/c ratio as 0.5, 0.6, and 0.7 and was used to verify the performance of *Bacillus sphaericus* carbonate precipitation. The result shows that the based-on porosity, reduction of water absorption of specimens was in the range of 65 to 90% [10]. The enhancement in durability and water tightness due to precipitation of calcite in the cracks was used to achieve self-healing of concrete [11].

The detailed study for the repair of cracks in concrete using various methods was mentioned [12]. Most of the above-referred study mentions regain in compressive strength and reduction of permeability as an indicator for crack repair effectiveness using MICP. Also limited research on remediation of realistic cracks and widely varied procedures adopted by researchers. Application of MICP in the field of building material, preservation of monuments and soil bio clogging was highlighted by Joshi et al., (2017) [13]. He concludes that the application of MICP is effective for self-healing of cracks in concrete and mortar. Use of *Bacillus sphaericus* with sodium alginate was employed during concrete mixing and hardening by adopting three techniques such as freeze-drying, extrusion, and spray drying [14]. Enhancement of mechanical properties of concrete such as split tensile, compressive and flexural strength and reduction in permeability, water absorption, sulphate ion concentration and volume of voids, by using MICP techniques [15, 16]. Use of ureolytic and non-ureolytic bacteria in recycled aggregate and recycled aggregate concrete to reduce the water absorption and increase in specific gravity of the material [17]. The development of cracks in concrete is a symptom of weakness in the tensile strength of concrete. Evaluation of the effectiveness of cracks repairs through split tensile strength (STS) and the amount of  $\text{CaCO}_3$  precipitation as an indicator has focused the objective of this research.

This paper hereby aims to determine the filling of generated crack width by using MICP and its efficacy of repair. The study encompasses a reduction in permeability, a percentage amount of  $\text{CaCO}_3$  precipitation the cracks and recoups of the tensile strength of cracked mortar after implementation of proposed MICP treatment.

## 2. Materials and Sample Preparation

Figure 1 represent the basic flowchart which gives detail information about the selection of bacteria and its cultivation of culture. Preparation of desired molarity cementation solution of  $\text{CaCl}_2$  using standard OPC cement, locally available sand with desired water cement ratio. Cement mortar was prepared by using this mixture. Artificial cracks were generated as mentioned in section 2.2. and followed by MICP treatment. The repaired sample were tested for permeability and spilt tensile test using standard methods.

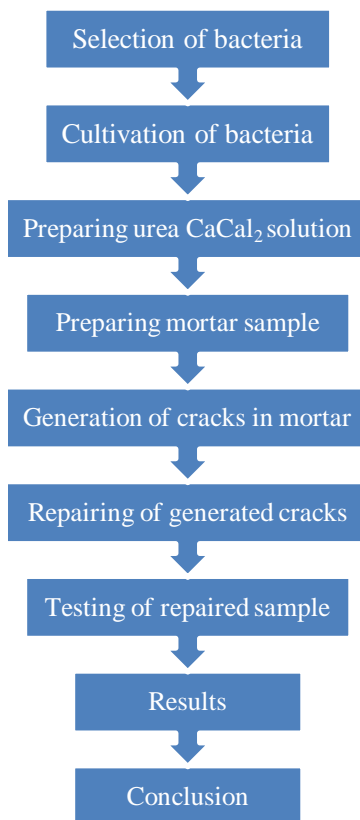


Figure 1. Represent flow diagram of the overall process followed

### 2.1. Bacterial Culture and Cultivation

Due to the high urease activity of *Bacillus pasteurii* or *Sporosarcinapasteurii*, these microbes are extensively preferred to produce a high amount of precipitates within a short period of time [18]. Bacterial culture of *Bacillus Pasteurii* NCIM 2477 shown in Figure 2(a) was collected from the National Collection of Industrial Microorganism, Pune, Maharashtra (India). *Bacillus Pasteurii* is cultivated in the laboratory using nutrient agar media with protocol and instruction mentioned on the container of culture medium. 20 grams of agar and four grams of nutrient agar powder were mixed well in 250 ml distilled water and the pH was adjusted between 7 to 7.5. The Nutrient agar solution was then heated up to boiling point  $100^\circ\text{C}$  using the heater. The autoclave was used for sterilization of nutrient solution and other glassware. Figure 2(b) shows the Cultivation of culture.

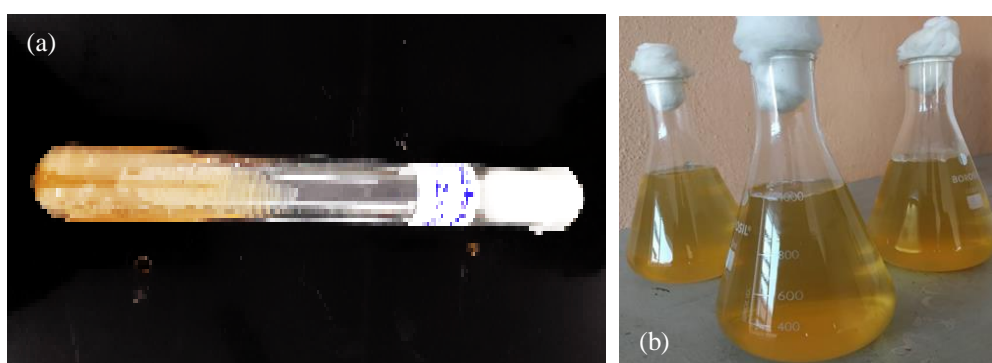


Figure 2. (a) Bacterial culture; (b) Cultivation of culture (microorganism)

## 2.2. Preparation of Cementation Solution

Ureolytic driven calcite precipitation was achieved by using urea calcium cementation media. From the AR grade of urea and calcium chloride ( $\text{CaCl}_2$ ) were used. For complete production of calcite, molecular weights of urea ( $\text{CO}(\text{NH}_2)_2$ ) and anhydrous calcium chloride ( $\text{CaCl}_2$ ) is approximately 60.06 g/mole and 111 g/mole, respectively. The cementation solution of 0.25 M of concentration was made by dissolving 15.1 g of urea (solid) and 27.75 g of anhydrous  $\text{CaCl}_2$  (solid) into 1 liter of water. To facilitate precipitation of small size and strong calcium carbonate which can penetrate in small cracks, a low chemical concentration was used as suggested by Al Qabany et al. (2013) [19].

## 2.3. Preparation of Mortar Specimens

Type I ordinary Portland cement (OPC) of 53 grade, river sand, and distilled water were used to prepare mortar. Figure 3a illustrates the grading curve of sand used. The cement had a specific gravity of 3.12, normal consistency 29%, bulk density  $1400 \text{ Kg/m}^3$  and Blaine fineness  $330 \text{ m}^2/\text{kg}$ . The sand had a specific gravity of 2.68 and a fineness modulus of 2.62 and density  $1600 \text{ Kg/m}^3$ . The water-to-cement (w/c) ratio was 0.4 and the sand-to-cement (s/c) ratio was 3.0. To prepare a homogeneous mix of the mortar, the cement was first added into water and mixed by hand for 2 min followed by sand mixing for another 2 min. Thin plastic pipes (45 mm in diameter and 90 mm in height) were used for casting. Two half rods of 10 mm diameter and 90 mm length were placed in molds to ensure single and straight crack in the sample. The freshly mixed mortar was poured into these molds as shown in Figure 3b, in two layers, and each layer of all samples was compacted to the equal desired density. After casting, the mortar samples were sealed and placed in a lab environment ( $24$  to  $26^\circ\text{C}$ ) for 28 days for curing. At the age of 28 days, three virgin samples (ST1, ST2, ST3) were tested for split tensile strength according to IS-5816-1999 and the rest cylinder samples were cut to develop/gain different crack sizes and then to perform crack repair.

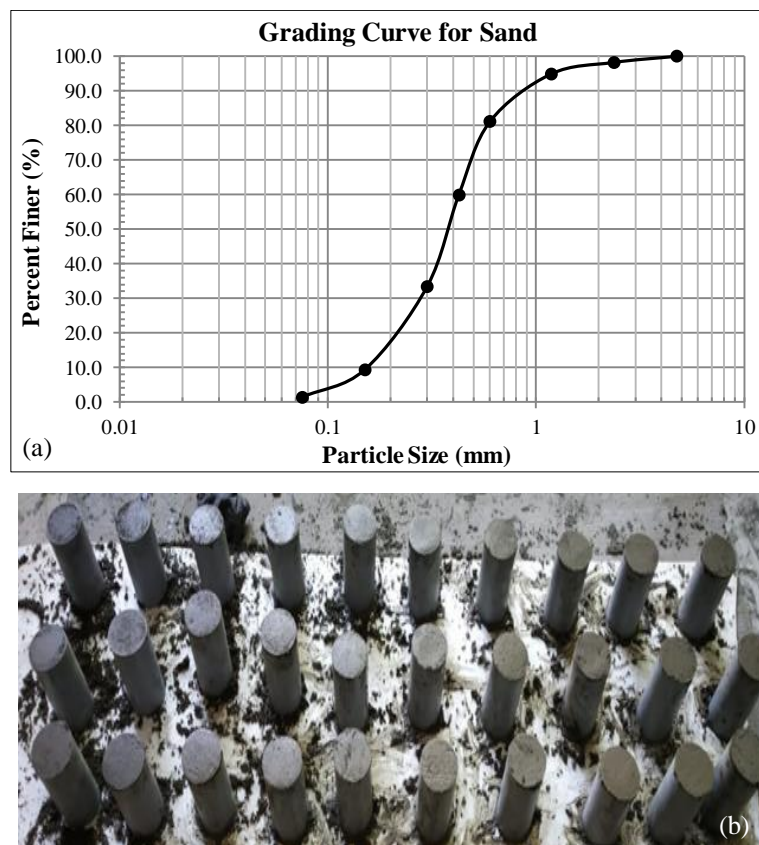


Figure 3. (a) Prepared mortar samples; (b) Grading Curve

## 2.4. Generation of Cracks in Mortar Specimens

In the process of generation of artificial cracks of different sizes in all 10 mortar samples, end portions were trimmed by 10 mm and the middle 80 mm was cut in equal two half with their plastic molds on, each of 45 mm diameter and 40 mm in length. These, 20 short discs samples were split to have different crack widths using a jaw clamp as shown in Figure 4. A sample crack generated is shown in Figure 5. A small clamping arrangement was made to keep crack open, and photographs of both end cross-section were taken. At the end of 28 days, small clamps were removed, and crack repair work was initiated.



Figure 4. Crack generation

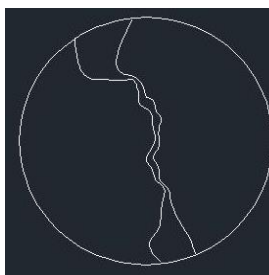
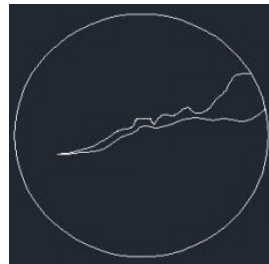
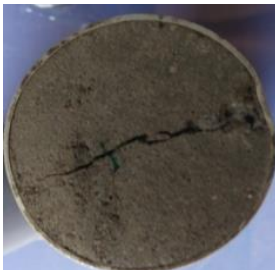
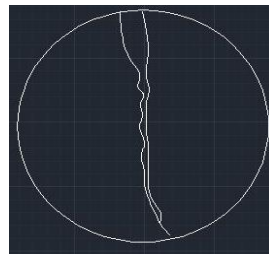
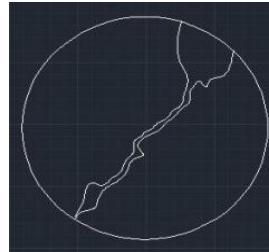
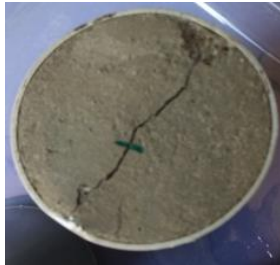
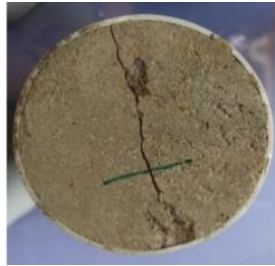


Figure 5. Camera picture

Figure 6. Image through CAD

Figures 5 and 6 show a photograph and the features received through CAD respectively for a few samples. A photography examination was done to understand the size and pattern of cracks generated. The photo images were then inputted to (CAD) to characterize the crack features and compute crack areas and widths. For a correct representation of crack width and to account for irregularity of cracks at two ends of the disc, the average crack size of the two ends was used and further calculation was made using the Equations 3 and 4.

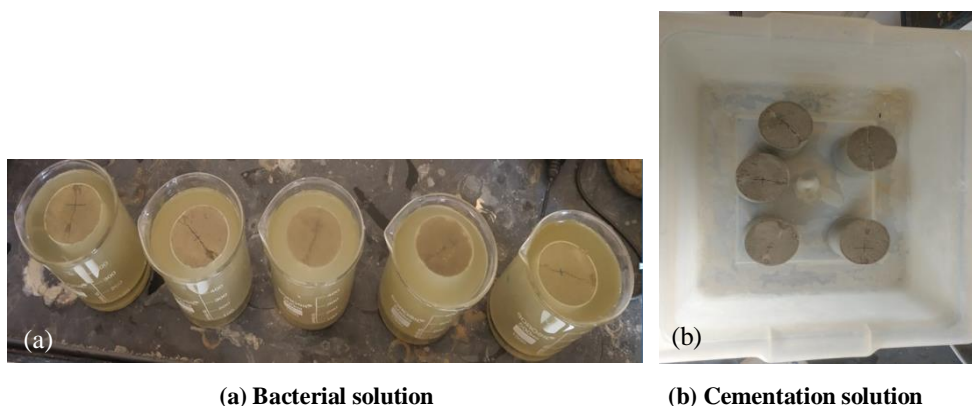
$$\text{Crack area (\%)} = \frac{\text{crack area}}{\text{sample cross section area}} \times 100\% \quad (3)$$

$$\text{Crack width (mm)} = \frac{\text{average crack area}}{\text{average crack length}} \quad (4)$$

The four samples (UTC1 to UTC4) out of 20, with the average crack width in the range 0.16 mm to 1.55 mm, were placed in distilled water for 24 days to understand autogenously crack healing of mortar. These samples are referred to henceforth as untreated samples. The balances of sixteen samples (TC1 to TC16), with the average crack width ranging from 0.12 to 1.30 mm, were used for the MICP repair tests which were treated with MICP.

## 2.5. Crack Repair

MICP treatment for sixteen samples was performed in bacterium solution and urea-CaCl<sub>2</sub> solution at room temperature 30 ± 2°C. Each cracked sample was soaked in bacterium solution for 2 hours as shown in Figure 7(a) and allowed the samples to saturate. After taking out from the bacterium solution, samples were made to drain off. Then all these samples were put in a container having urea-CaCl<sub>2</sub> cementation solution as shown in Figure 7(b) hours for the MICP process to happen. These 24 hours is counted as one round of treatment. The whole assembly of the sample with cementation solution was kept circulating with the help of a plate and stirrer bar. Repeat all these steps for the next 8, 16, 24 rounds of the treatment.



(a) Bacterial solution

(b) Cementation solution

Figure 7. Soaking of samples

## 3. Test and Methods

### 3.1. Water Permeability

Permeability test on all sixteen samples was conducted using the constant head method as per IS-2720 (Part17)1986 to find the efficacy of repair using MICP treatment and curing period concerning crack width. All samples were soaked in water for 24 hours for saturation before conducting the permeability test. A sample of 45 mm diameter and 40 mm length was trimmed at the end to just fit at bottom of transparent graduated glass pipe of 45 mm diameter, 150 mm height. The proper arrangement was made to seal the joints of the pipe and specimen. This assembly of permeability mould as shown in Figure 8(a) and experimental set up shown in Figure 8(b). Tap water was continuously filled in a glass pipe to maintain a constant head with a proper outlet for overflow. The volume of water flowing out from the container and corresponding time was recorded to calculate the coefficient of permeability  $k$  using the formula mentioned in Equation 5.

$$k = \frac{qL}{Ah} \quad (5)$$

Where  $k$  = Coefficient of permeability in mm/sec;  $q$  = discharge in mm<sup>3</sup>/sec;  $L$  = Length of specimen in mm;  $A$  = Cross-sectional area of specimen in mm<sup>2</sup> and  $h$  = Constant head in mm.

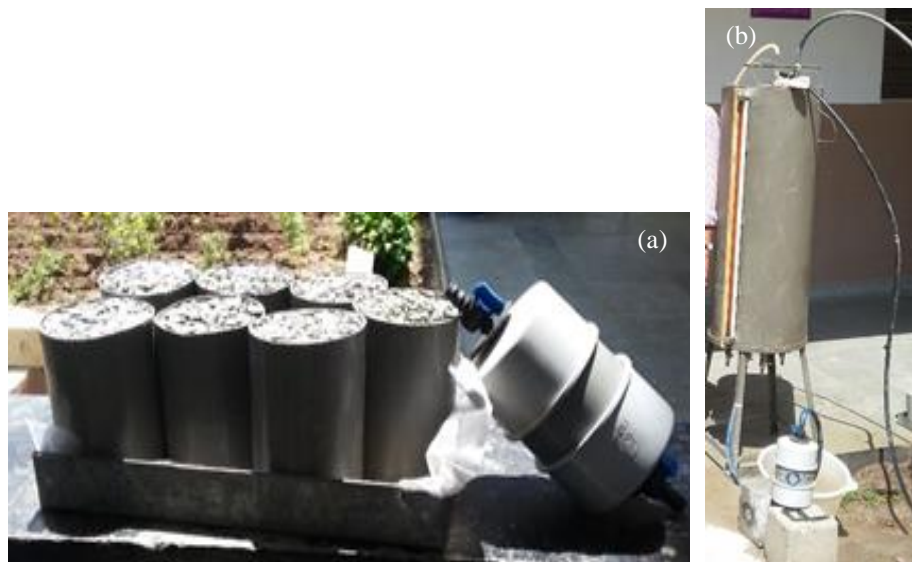


Figure 8. (a) Permeability sample mould; (b) Experimental setup for permeability test

### 3.2. Splitting Tensile Strength (STS)

At the end of 28 days, three virgin samples (ST1, ST2, ST3) of 45 mm diameter and 90 mm in height which were not subjected to MICP treatment, were tested for STS according to IS 5816-1999. Sixteen samples (TC1 to TC16) were split to gain different sizes of crack and then used for crack repair using MICP treatment and four samples (UTC1 to UTC4) as control samples without MICP treatment. These sixteen (TC1 to TC16) were dried under an ambient environment for two days and tested for STS as per IS 5816-1999. The amount of CaCO<sub>3</sub> deposited on both end fractured surfaces were measured and expressed as percent of the total fractured surface area.

## 4. Results and Discussion

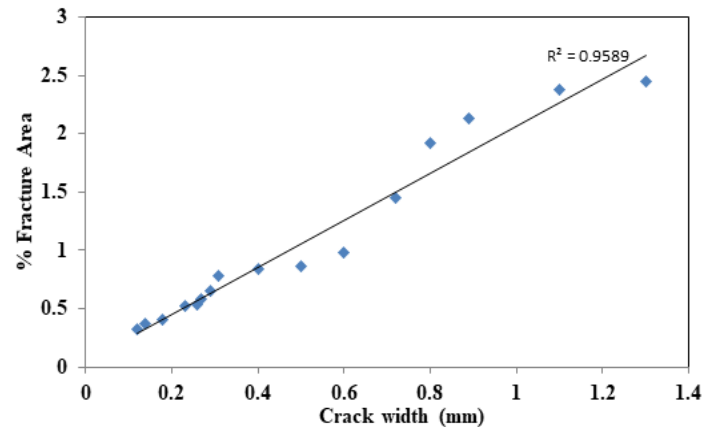
Permeability test on all sixteen samples was conducted using the constant head method as per IS2720-1986 (Part17) to find the efficacy of repair using MICP treatment and curing period concerning crack width. All samples were soaked in water for 24 hours; the results obtained for sixteen MICP treated samples through permeability, STS and percent of precipitated CaCO<sub>3</sub> are summarized in Table 1. Table 2 depicts the results of permeability on four untreated samples. Figure 9 illustrate the linear relation of crack width generated and percent of fractured area. Figure 9, illustrate that crack width is directly proportional to percent of fractured area. Figure 9 satisfies strong linear association among the crack width and fractured area.

Table 1. Test result of MICP treated samples

MICP Treated Sample	Original fracture		Permeability (mm/sec)				Overall percent of reduction	STS (kPa) at 24 <sup>th</sup> round	% of CaCO <sub>3</sub> at 24 <sup>th</sup> round
	% Fracture Area	Ave. width (mm)	0 round	8 <sup>th</sup> round	16 <sup>th</sup> round	24 <sup>th</sup> round			
TC1	0.32	0.12	0.008335	0.002812	0.002104	0.001853	77.76845	43.26	4.95
TC2	0.37	0.14	0.01652	0.005967	0.004717	0.004175	74.72859	29.85	5.13
TC3	0.41	0.18	0.1157	0.03697	0.029283	0.02589	77.62316	33.85	4.12
TC4	0.52	0.23	0.1312	0.04889	0.03857	0.03521	73.16311	45.2	4.68
TC5	0.54	0.26	0.1473	0.04825	0.03693	0.032271	78.09165	51.91	6.73
TC6	0.58	0.27	0.1587	0.05812	0.04812	0.04136	73.93825	95.32	7.19
TC7	0.65	0.29	0.1868	0.06867	0.05054	0.04869	73.93469	122.34	15.68
TC8	0.78	0.31	0.28689	0.08912	0.07012	0.06839	76.1616	128.38	17.32
TC9	0.84	0.4	0.3768	0.151869	0.11104	0.08945	76.26062	148.44	21.14
TC10	0.87	0.5	0.6107	0.265946	0.208238	0.13674	77.6093	178.32	19.46
TC11	0.98	0.6	0.7532	0.29678	0.22985	0.147851	80.37029	195.67	20.08
TC12	1.45	0.72	0.9476	0.41935	0.28745	0.2003	78.86239	242.58	52.32
TC13	1.92	0.8	1.1254	0.37384	0.27758	0.1712	84.78763	275.82	65.84
TC14	2.13	0.89	1.2147	0.43748	0.30367	0.19894	83.62229	292.38	79.25
TC15	2.38	1.1	1.3254	0.53858	0.32756	0.25131	81.03893	380.5	82.34
TC16	2.45	1.3	1.4721	0.81367	0.62576	0.51576	64.96434	311.58	69.27

**Table 2. Test result of Untreated (controlled) samples for autogenous healing**

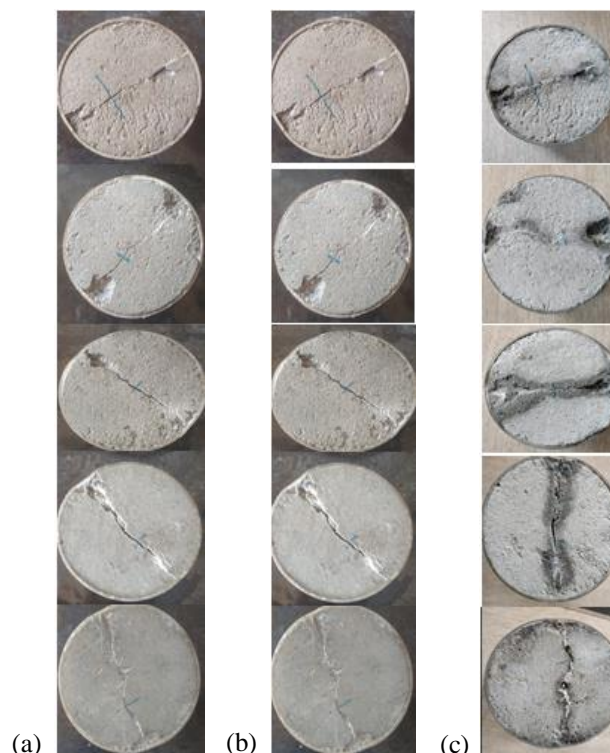
Untreated sample (Soaked in water only)	Original fracture		Permeability (mm/sec)			
	% Fraction Area	Ave. crack width (mm)	0 Round	8 <sup>th</sup> Round	16 <sup>th</sup> Round	24 <sup>th</sup> Round
UTC1	0.43	0.16	0.08053	0.067258	0.06136	0.06013
UTC2	0.82	0.3	0.19751	0.17145	0.1648	0.1596
UTC3	1.37	0.76	1.01637	0.8983	0.86771	0.85472
UTC4	2.47	1.55	1.98531	1.84654	1.780194	1.75483



**Figure 9. Generated crack width Vs % fracture area of mortar sample**

**4.1. Crack Healing**

Progress of crack healing at different rounds for the representative sample is shown in Figure 10. It is observed from Figure 10, that due to MICP treatment, cracks are gradually healed over the number of treatment round. Healing of cracks varies with the percent of precipitation of CaCO<sub>3</sub>. Smaller cracks get healed at earlier round. It is to note that internal cracks could not get repaired 100% in spite of precipitation of a sufficient quantity of CaCO<sub>3</sub>. Table 1 depicts that, for the sample TC15, the maximum percent of deposition of CaCO<sub>3</sub> on the cracked surface was 82.34 rather than 100%. Also, negligible healing of crack is observed in samples (UTC1 to UTC4) which are untreated (soaked in water only). Similar report has been mentioned by author Chen et al. (2019) [20] that MICP can effectively use for healing of crack due to deposition of calcium carbonate deposition.



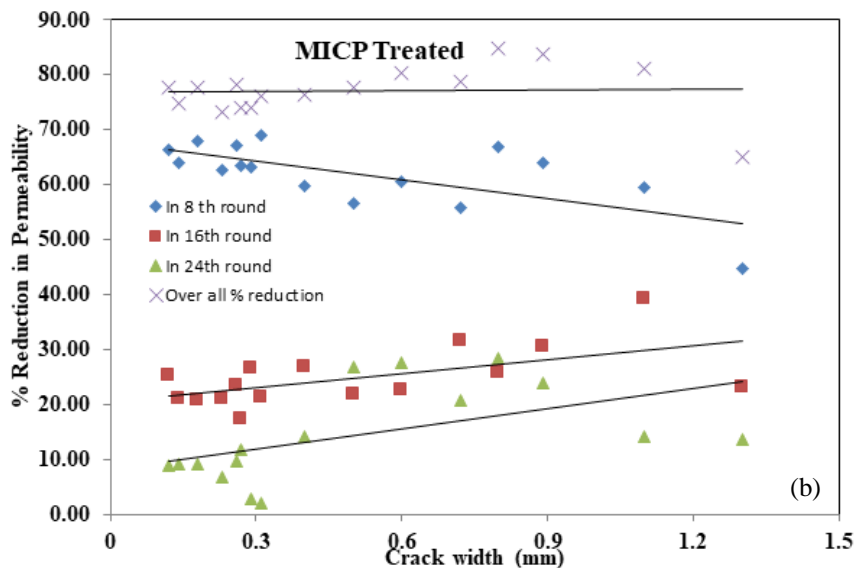
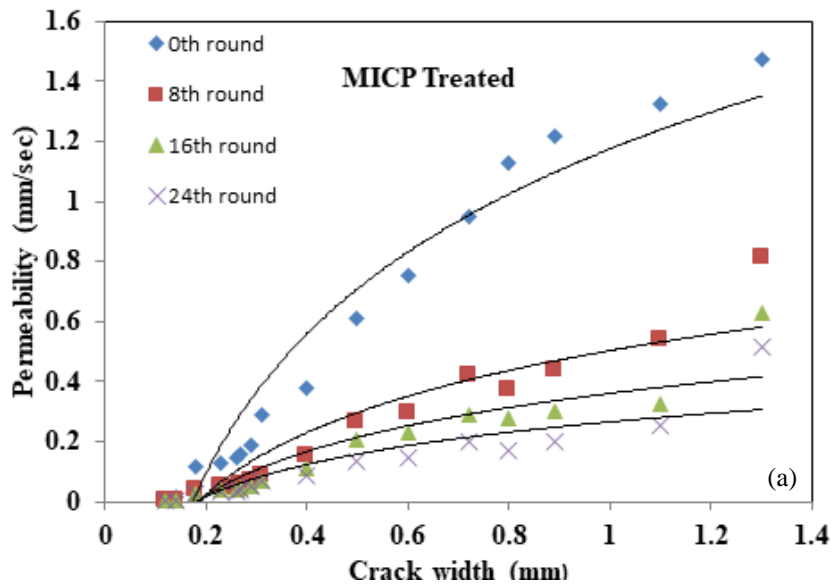
**Figure 10. Cracks repairs at different rounds of MICP treatments. (a) At 8th round; (b) At 16th round; (c) At 24th round**



4.2. Permeability

Figure 11(a) and 11(b) and Tables 1 and 2 represent crack repairing performance of MICP treated and untreated mortar samples on permeability respectively. Increase in permeability with an increase in average crack width, as seen in Figure 11(a). As crack width increases from 0.12 mm to 1.3 mm, permeability has increased from 0.008335 mm/sec to 1.4721 mm/sec. The authors are of opinion that results obtained are in line with Tittelboom et al. (2010) [1] in which the average crack width of the split cylinder increased from 0.15 to 0.30 has resulted in an increase in permeability from 0.05 mm/sec to 0.5 mm/sec. In the present study crack width ranges from 0.12 to 1.3 mm. The slope of (permeability vs crack width, Figure 11(a) curve is steeper for 0<sup>th</sup> round in comparison with the 24<sup>th</sup> round of MICP. Also, Figure 11(b) depicts an average 60% reduction in permeability of all cracked samples at end of 8<sup>th</sup> round after MICP treatment. The however smaller rate of reduction in permeability was observed at the end of 16<sup>th</sup> (25%) and 24<sup>th</sup> (14%) round respectively. This point out the percent of healing of cracks is faster up to 8<sup>th</sup> round and it slows down thereafter. This could happen because of the amount and dissemination of CaCO<sub>3</sub> in the cracks which have reduced permeability. At the end of the 24<sup>th</sup> round, the maximum reduction was in the range 73 to 85% as that of 0<sup>th</sup> round, indicating, 100% reduction in permeability could not be achieved because of the non-healing of all cracks.

From the above discussion, it is cleared that, number of MICP treatment rounds influences the reduction of permeability. Also, a higher rate of decrease in permeability at an early stage (8th cycle) as compared to the lower rate of decrease with an increase in the number of the round. Sample with wider cracks will have a higher rate of decrease in permeability as compared with fine cracks. This could happen because of more MICP solution can easily penetrate through wider cracks and deposits CaCO<sub>3</sub>. On the contrary small cracks get plugged at the early stage of treatment. A decrease in R-squared values of curves in Figure 11(a) from 0.93 (0<sup>th</sup> round) to 0.75 (24<sup>th</sup> round) might be due to the amount and size of precipitated CaCO<sub>3</sub> in the cracks.



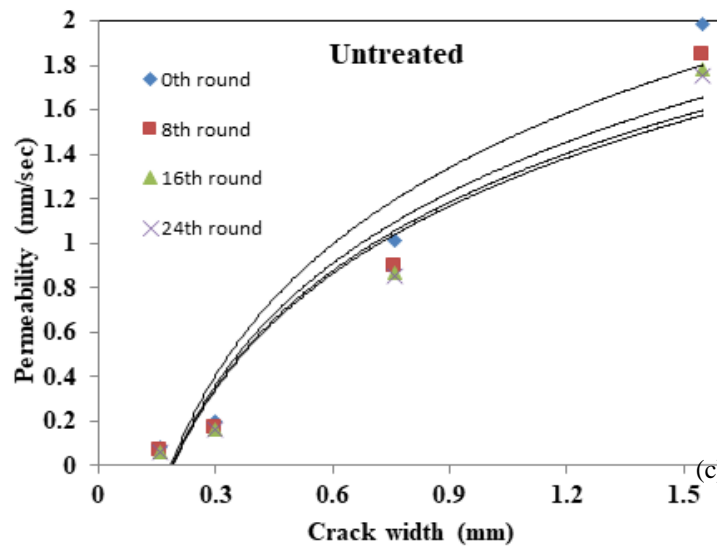


Figure 11. (a) Repaired specimens using MICP treatment (b) % reduction in permeability (c) Permeability results for untreated specimens (soaked in water only)

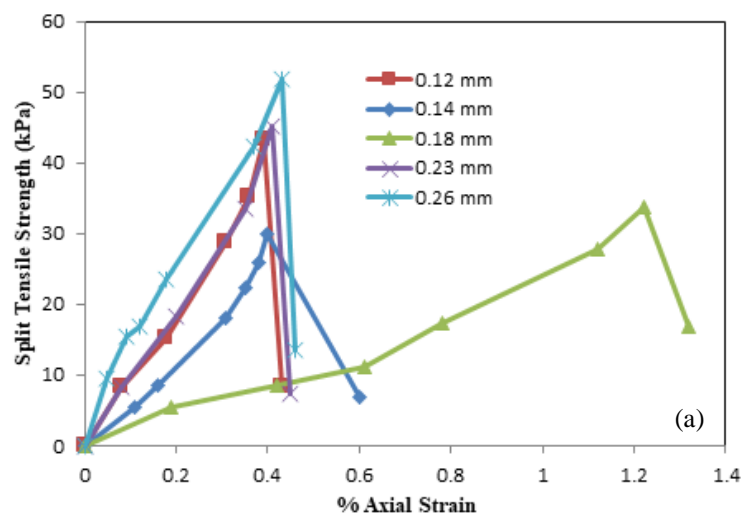
Figure 11 represents crack repairing performance of untreated (soaked in water only) mortar samples on permeability. The decrease in permeability up to 25% for the sample (UTC1) with fine 0.16 mm average crack width, from 0.08053 mm/sec at 0th round to 0.06013 mm/sec at 24<sup>th</sup> round could be the result of autogenous healing due to hydration of cement [18]. As anticipated for sample (UTC4) with a major crack of 1.55 mm, reduction in permeability on account of autogenous healing due to hydration of cement was negligible (11%).

### 4.3. Split Tensile Strength

The results of STS conducted on three virgin samples (ST1, ST2, ST3) at the age of 28 days, was 3674±126 kPa. This test was also conducted on MICP treated samples (TC1 to TC16) at the end of the 24<sup>th</sup> round. However, the test could not be possible on the untreated sample (UTC1 to UTC4) as it fails immediately on the application of negligible load. This could be because of insufficient binding developed due to the autogenous healing of cracks. The results obtained from the split tension test on TC1 to TC16 samples are shown in Figure 12. Based on these following findings are noted.

- There is no co-relation of crack width on STS. The maximum values of STS were in the range of 29.85kPa to 380.5 kPa, almost 10% of the virgin sample (3674 kPa).
- The majority of the MICP treated sample has shown linear stress-strain behaviour with brittle failure at various axial strains.

It is presumed that the lower value of STS could be because of insufficient healing of cracks imperfect bonding developed among the cracked sample. Relationships between the STS, crack width, and percent of precipitation of CaCO<sub>3</sub> on the fractured crack surface and effectiveness of crack healing by MICP were studied. A similar result has been found by the potential application of bacteria for improvement of the split tensile test of concrete over the conventional concrete by the researcher Gavimath et al. (2012) [21].



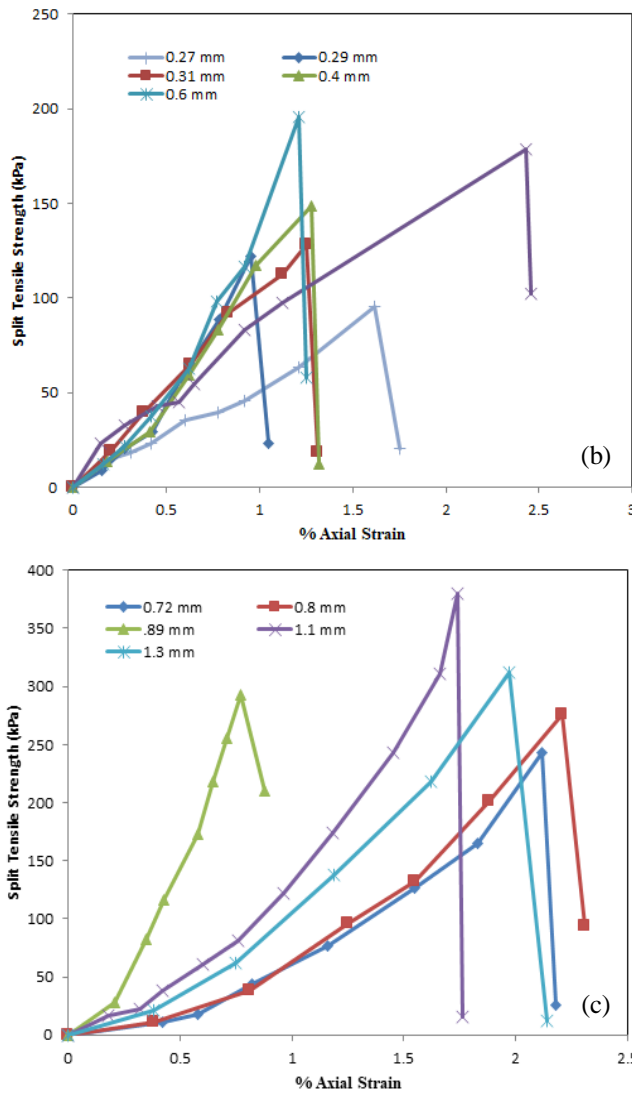
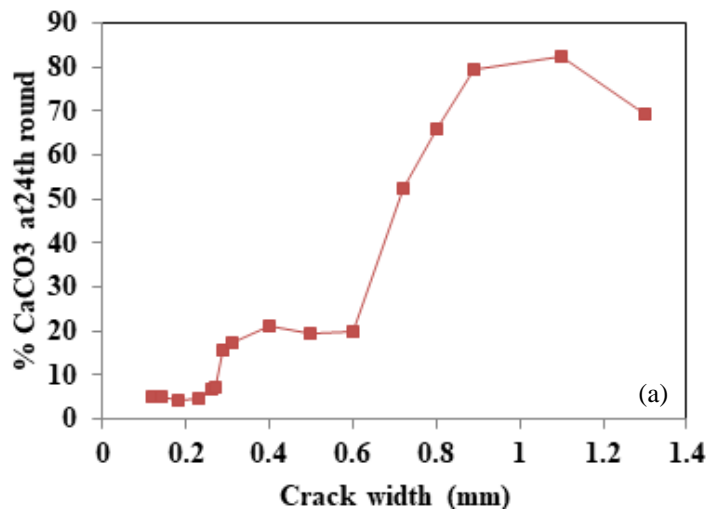


Figure 12. (a) Crack width from 0.12-0.26 mm; (b) Crack width from 0.27-0.6 mm; (c) Crack width from 0.72-1.1 mm

Figures 12(a) to 12(c) STS vs strain curves for repaired specimens with different crack widths. Figure 13 (a), depicts the graphical presentation of the amount of CaCO<sub>3</sub> precipitated Vs. crack width. A peanut swing from 4.12 to 7.19% in calcium carbonate deposition is seen in a region I, where crack width is less than 0.27 mm. This could be due to minimal entry of bacteria or cementation solution in small cracks followed by 15 to 20% increase in CaCO<sub>3</sub> in region II of crack width 0.29 to 0.6 mm. Substantial increases in region III (52 to 82%) imply that the favorable crack width for repair through MICP is 0.72 to 1.1 mm. For region IV for 1.3 mm crack, an unexpected slight decrease in CaCO<sub>3</sub> may be due to unidentified reasons.



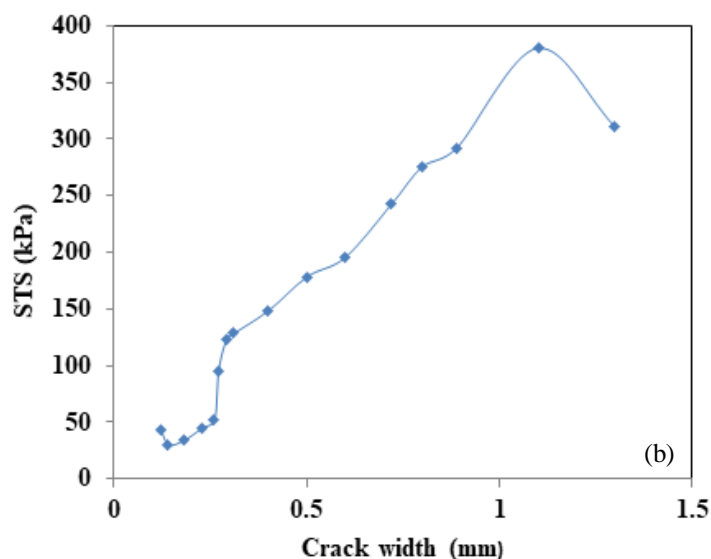


Figure 13. (a) Crack width % vs.  $\text{CaCO}_3$ ; (b) Crack width vs. STS

The relationship between STS and crack width as shown in Figure 13(b) indicates that in the region I for crack width less than 0.29 mm, there is no clear co-relation. This could be because of quick sealing of small cracks might have stopped the entry of bacteria and cementation solution resulting in lower values of STS. Exactly reverse of this is observed in the region III, despite large crack width (1.3mm), STS has decreased (311 kPa) over prior values (380 kPa). One of the causes could be insufficient sticking/formation of the bond between cracks and smaller size and microstructure of distribution of  $\text{CaCO}_3$ . This indicates from region II that, 0.31 to 1.1 mm crack width sizes in mortar can be effectively repaired by MICP.

## 5. Conclusions

The present study investigates the following

- Generated cracks in cement mortar can be repaired/healed by MICP. The performance of healing increases with an increase in treatment rounds. Almost all cracks rapidly get repaired in the first 8<sup>th</sup> round and thereafter process of healing becomes slower.
- The smallest and largest crack width was 0.12 and 1.3 mm respectively. The percent of reduction in permeability for the cracks ranging from 0.12 to 1.3 mm was in the range from 65 to 85%. The initial permeability of the smallest crack width was 0.008335 mm/sec which has reduced to 0.002812 mm/sec in 8<sup>th</sup> round, 0.002104 mm/sec in 16<sup>th</sup> and 0.001853 mm/sec in 24<sup>th</sup> round. While for the largest crack of width, reduction in permeability was from 1.4721 to 0.81367 mm/sec in 8<sup>th</sup> round, 0.62576 mm/sec in 16<sup>th</sup> round followed by 0.51576 mm/sec in 24<sup>th</sup> round. A maximum percent of reduction in permeability was observed for crack width of 0.8 mm which is from 1.1254 mm/sec to 0.37384 at 8<sup>th</sup> round, and 0.27758 to 0.1712 mm/sec at 16<sup>th</sup> and 24<sup>th</sup> round respectively.
- For untreated specimen having small crack width (0.16 mm), a considerable reduction in permeability took place in the first 8<sup>th</sup> round as compared to a large crack width of 1.55mm. This implies autogenously crack healing due to hydration of cement is more prominent in a small crack in comparison to larger crack width. The percent of reduction in permeability through autogenously crack healing was 25 to 11% for 0.16 and 1.55 mm crack width respectively.
- The results of STS conducted on three virgin samples (ST1, ST2, ST3) were  $3674 \pm 126$  kPa while on MICP treated samples (TC1 to TC16) it varies in the range 43 to 380 kPa i.e. 1 to 10% of virgin samples. Conventional failure of concrete mortar is at 3% axial strain with stress-strain behaviour as linear. In our case, most of MICP repaired specimens of small crack (0.12 to 0.26 mm) have failed at axial strain less than 1% and specimens with larger crack (0.5 to 1.3 mm) at axial strain more than 2%, indicating a good improvement in repair after MICP treatment.
- Based on the test results obtained for percent of deposition of  $\text{CaCO}_3$ , STS, axial strain at failure, it implies, repairs through MICP is most effective for the size of cracks width within the range of 0.29 to 1.1 mm crack width.

## 6. Conflicts of Interest

The authors declare no conflict of interest.

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