Enhancing Eco2GC Drain Cover through Microbial Self-Healing Concrete: Mechanical, Crack-Healing and Microstructural Performance

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***Abstract*— This study investigates the integration of Bacillus subtilis-based microbial self-healing concrete into the Eco2GC Drain Cover to enhance crack-healing capability while maintaining mechanical performance. M40 concrete with a nominal mix ratio of 1:1.5:3 and a water-to-cement ratio of 0.40 was prepared with microbial agent contents of 0% (M0), 3% (M3), and 5% (M5) by cement weight. Compressive strength was evaluated at 7, 14, and 28 days, while controlled-crack specimens were subjected to water and soil curing to assess self-healing development. Scanning Electron Microscopy (SEM) was employed to examine microstructural changes and mineral-like deposits within the crack regions. The experimental framework enables comparison of microbial dosage and curing environment in relation to mechanical performance, crack-healing behaviour, and microstructural characteristics. The findings provide a scientific basis for developing Eco2GC Drain Cover from a conventional drainage component into a more durable concrete element with autonomous crack-repair potential.**

***Keywords*— Eco2GC Drain Cover; Bacillus subtilis; microbial self-healing concrete; crack healing; microstructural analysis.**

I. INTRODUCTION

Drainage systems form an essential part of environmental infrastructure, providing a controlled pathway for surface runoff and helping to minimise water accumulation. Their overall performance, however, is influenced not only by the hydraulic capacity of the drainage channel but also by the design, functionality and durability of individual components, particularly the drain cover. The Eco2GC Drain Cover was therefore developed as a concrete-based component designed to maintain water flow while limiting the entry of debris such as soil, sand, leaves, twigs and other solid waste into the drainage channel. By reducing the amount of debris entering the drain, the proposed cover has the potential to minimise blockage and ease routine maintenance. Previous evaluation of the Eco2GC Drain Cover recorded an average flow rate of 0.199 L/s, which was comparable to the 0.201 L/s measured for a conventional drain cover. The product also achieved an average 28-day compressive strength of 43.63 N/mm². Despite these encouraging results, cracking remains an important durability concern for concrete components operating in drainage environments. Cracks that develop during service may provide pathways for water and aggressive substances to penetrate the concrete, potentially accelerating deterioration and reducing its long-term durability [1]–[3].

Advances in concrete technology have led to growing interest in microbial self-healing as an alternative approach for repairing cracks and improving the long-term performance of cementitious materials. This technique is commonly associated with Microbially Induced Calcium Carbonate Precipitation (MICP), in which microbial activity promotes the formation of mineral precipitates, particularly calcium carbonate ($CaCO_3$), within cracks and voids [1], [2], [4]. The resulting mineral deposition may contribute to crack closure, thereby limiting pathways for water and other potentially harmful substances to penetrate the concrete. Nevertheless, the performance of microbial self-healing concrete is not governed by bacterial activity alone. Factors such as

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bacterial species and concentration, incorporation technique, curing regime, crack characteristics and surrounding environmental conditions can substantially influence the healing response [2]–[5]. In particular, parameters such as pH, temperature and moisture availability are frequently identified as important factors affecting bacterial viability and biomineralisation within the concrete matrix. Therefore, appropriate selection of the microbial system and exposure conditions is essential when evaluating the effectiveness of microbial self-healing concrete.

Although microbial self-healing concrete has received considerable research attention, previous studies have largely examined its mechanical properties, durability, biomineralisation and crack-healing behaviour using laboratory-scale concrete or mortar specimens [2]–[6]. Comparatively less attention has been given to its incorporation into functional concrete products intended for drainage applications. Consequently, it remains unclear whether microbial-based healing can be introduced into such components to enhance crack recovery while maintaining the mechanical properties required for practical use.

To address this gap, the present study incorporates a *Bacillus subtilis*-based microbial agent into the concrete used for the Eco2GC Drain Cover. This approach extends the original function of the product beyond that of a conventional drainage component by introducing a self-healing capability aimed at improving its response to crack formation. Concrete containing 0%, 3% and 5% microbial agent by cement weight was investigated to determine changes in compressive strength, crack-healing behaviour and microstructural characteristics. The healing response was also examined under water and soil curing conditions to establish whether the surrounding curing environment influences crack recovery. Through these investigations, the study provides experimental evidence on the feasibility of incorporating microbial self-healing technology into the Eco2GC Drain Cover and its potential contribution towards improving the long-term durability of the product.

IILITERATURE REVIEW

Microbial self-healing concrete has attracted increasing research interest as a means of improving concrete durability through biologically mediated crack repair. Unlike autogenous healing, which mainly occurs through continued hydration of unhydrated cement particles and other naturally occurring reactions within the cementitious matrix, microbial healing relies on the metabolic activity of microorganisms to promote mineral formation within cracks [1], [2]. One of the most commonly reported mechanisms is Microbially Induced Calcium Carbonate Precipitation (MICP), whereby microbial activity facilitates the precipitation of calcium carbonate ($CaCO_3$) on crack surfaces and within the crack region [2], [3]. The accumulation of these mineral products can progressively seal the damaged area, although the extent of healing depends strongly on the conditions surrounding the microorganisms.

Moisture availability is particularly important because microbial activity and mineral precipitation require a suitable environment for the healing process to occur. Under favourable conditions, the resulting mineral deposits may occupy voids and cracks within the concrete matrix and contribute to gradual crack closure [2], [3]. Species belonging to the genus *Bacillus*, including *Bacillus subtilis*, have frequently been investigated for this purpose because of their ability to withstand the relatively harsh conditions found in cementitious materials and participate in biomineralisation processes [3]. Nevertheless, bacterial species alone do not determine the effectiveness of the healing response. Bacterial concentration, pH, temperature, nutrient availability, incorporation technique, curing regime and crack characteristics may each influence microbial activity and the subsequent formation of healing products [2]–[4]. Javeed et al. [3], for example, identified pH, temperature, cell concentration and the method of bacterial incorporation as important parameters governing microbial self-healing performance.

The effects of microbial activity are also relevant to the mechanical and microstructural properties of concrete. Mineral precipitation within cracks and pore spaces may modify the internal structure of the cementitious matrix, potentially influencing its density and mechanical behaviour. Improvements in crack closure, however, do not necessarily correspond to an increase in strength. The mechanical response may vary according to factors such as bacterial concentration, microbial incorporation method and concrete mix composition [3], [6]. For this reason, microbial self-healing should be evaluated through both healing performance and mechanical testing. Considering these aspects together provides a more reliable assessment of whether enhanced crack recovery can be achieved without adversely affecting the structural performance of the concrete.

For concrete used in underground or soil-contact applications, the surrounding environment can play an important role in determining the extent of crack healing. Hamza et al. [7] reported that soil conditions influenced the healing ratio of cementitious materials. Their findings further indicated that, in bio-mortar containing *Bacillus subtilis*, the introduced bacterial healing agent contributed more substantially to the

observed healing than microorganisms naturally present in the soil. These observations highlight the importance of considering the curing environment when assessing microbial-based crack repair. Accordingly, water and soil curing were selected in the present study to examine whether different exposure conditions produce distinguishable healing responses in microbial concrete.

Applying this concept to the Eco2GC Drain Cover introduces an additional function beyond its conventional role in drainage. By incorporating a *Bacillus subtilis*-based microbial agent into the concrete matrix, the drain cover is designed not only to perform its primary drainage function but also to promote crack repair when favourable conditions for microbial activity are present. The effectiveness of this approach is therefore evaluated through a combination of compressive strength testing, crack-healing observations and microstructural analysis. Examining these parameters together allows the healing response to be assessed alongside changes in material performance, providing a more comprehensive basis for determining the suitability of microbial self-healing technology for the Eco2GC Drain Cover.

III MATERIALS AND METHODS / METHODOLOGY

A. Eco2GC Drain Cover

The Eco2GC Drain Cover is a concrete-based drainage component designed to facilitate the passage of surface runoff into the drainage channel while restricting the entry of solid debris, including leaves, soil and litter, which may contribute to blockage. As illustrated in Fig. 1, the Eco2GC Drain Cover incorporates openings within its concrete surface to maintain water conveyance while providing a protective cover over the drainage channel. Previous evaluation of the original design recorded an average flow rate of 0.199 L/s, which was comparable to the 0.201 L/s measured for a conventional iron-type drain cover. Building on this existing design, the present study incorporates a *Bacillus subtilis*-based microbial agent into the concrete matrix to investigate whether microbial activity can promote crack healing while maintaining the required mechanical performance. This modification introduces a self-healing function to the Eco2GC concept, with the broader aim of enhancing the durability and extending the service life of the drain cover.



Fig 1 Eco2gc Drain Cover

B. Materials and Concrete Mix Preparation

An experimental programme was undertaken to investigate the incorporation of a *Bacillus subtilis*-based microbial agent into concrete developed for the Eco2GC Drain Cover, with particular emphasis on its crack-healing response and mechanical performance. The concrete was produced using cement, fine aggregate, coarse aggregate, water and a commercially available microbial product, Bacillus Care (Plant Probiotic), supplied by SHS Resources (M) Sdn. Bhd., Malaysia. *Bacillus subtilis* was selected because of its reported application in microbial concrete and its involvement in biomineralisation processes that may promote mineral precipitation within cracks [2], [3], [5]. Previous studies have also shown that microbial healing performance is governed by several factors, including bacterial species and concentration, incorporation technique and environmental exposure conditions [2], [3].

M40 concrete was prepared using a nominal cement-to-fine-aggregate-to-coarse-aggregate ratio of 1:1.5:3 and a water-to-cement ratio (w/c) of 0.40. Three mixtures were investigated and designated as M0, M3 and M5. M0 served as the control and contained no microbial agent, whereas M3 and M5 contained microbial agent at 3% and 5%, respectively, relative to the mass of cement. These concentrations were selected to examine whether increasing the microbial-agent dosage affected the compressive strength, crack-healing behaviour and microstructural characteristics of the concrete.

C. Experimental Design and Curing Conditions

The experimental programme initially comprised 54 self-healing specimens covering three microbial-agent dosages (M0, M3 and M5) and two curing environments (water and soil). For each mixture, 18 specimens were prepared, with nine assigned to water curing (W) and nine to soil curing (S). Three replicate specimens (n = 3) were allocated to each mixture–curing combination at Day 1, Day 14 and Day 28. This arrangement produced six experimental groups: M0-W, M0-S, M3-W, M3-S, M5-W and M5-S. The planned distribution of specimens is summarised in Table I.

TABLE I.

EXPERIMENTAL DESIGN OF MICROBIAL SELF-HEALING SPECIMENS

Code	Microbial agent (% by mass of cement)	Curing environment	No. of specimens		
			Day 1	Day 14	Day 28
M0-W	0%	Water	3	3	3
M0-S	0%	Soil	3	3	3
M3-W	3%	Water	3	3	3
M3-S	3%	Soil	3	3	3
M5-W	5%	Water	3	3	3
M5-S	5%	Soil	3	3	3
Total			18	18	18

Water and soil curing were selected to examine how different exposure environments affect the crack-healing behaviour of the concrete. Moisture availability and surrounding environmental conditions are particularly relevant to microbial activity and the subsequent formation of healing products within cracks [2], [3]. Soil curing was included to provide an exposure condition that is more representative of the intended application of the Eco2GC Drain Cover, where concrete may remain in contact with moist soil during service. This consideration is supported by Hamza et al. [7], who reported that soil conditions influenced crack healing in cementitious materials and observed that the introduced *Bacillus subtilis*-based healing agent made a greater contribution to the healing response of bio-mortar than microorganisms naturally present in the soil. The comparison between water and soil curing therefore provides a basis for examining whether the surrounding environment influences the healing response of the microbial concrete.

D. Controlled Crack Formation and Self-Healing Evaluation

Small-scale concrete specimens measuring 18 mm × 12 mm × 32 mm were prepared for the self-healing assessment. To produce consistent artificial cracks, aluminium sheets measuring 6 mm × 19 mm × 0.04 mm were used as crack inducers. Each sheet was positioned at a predetermined location during specimen preparation and carefully withdrawn approximately 5 to 6 hours after casting, leaving a controlled crack path within the concrete specimen.

Following crack induction, the specimens were transferred to their designated curing environments, either water or soil, according to the experimental groups described previously. The initial crack condition was documented at Day 1 and subsequently monitored at Days 14 and 28 to evaluate changes in crack appearance during the healing period. The 28-day observation period was adopted to allow progressive healing behaviour to be evaluated over time. A similar monitoring period was reported by Rahman et al. [8] in their investigation of Bacillus subtilis-based self-healing cement mortar, where healing performance was assessed for up to 28 days.

The experimental design initially included M0, M3 and M5 specimens. However, as described in the Results and Discussion section, the M5 specimens intended for crack-healing assessment were damaged during demoulding because sufficient early-age hardness had not developed. Consequently, the subsequent crack-healing evaluation was restricted to M0 and M3 under water and soil curing conditions.

E. Compressive Strength Test

Compressive strength was evaluated using 150 mm × 150 mm × 150 mm concrete cubes to investigate the effects of microbial-agent dosage and curing environment on strength development. Three mixtures were considered: M0 (0%), M3 (3%) and M5 (5%), with the microbial-agent dosage expressed relative to the mass of cement. Each mixture was subjected to two curing conditions, namely water (W) and soil (S). At each testing age of 7, 14 and 28 days, three replicate cubes (n = 3) were tested for every mixture–curing combination. This experimental arrangement resulted in 18 cubes per testing age and 54 cubes overall. The distribution of specimens according to mixture, curing condition and testing age is presented in Table II.

Compressive strength testing was included to determine whether microbial incorporation and the associated curing environment influenced the mechanical performance of the concrete. This consideration is particularly relevant to the Eco2GC Drain Cover, as any improvement in crack-healing behaviour should be achieved without compromising the strength required for its intended application. The results obtained for M0, M3 and M5 under water and soil curing were therefore compared at each testing age to examine changes in strength associated with microbial-agent dosage, curing condition and concrete age.

Testing was conducted in accordance with BS EN 12390-3, Testing hardened concrete — Part 3: Compressive strength of test specimens. Each cube was placed in the compression testing machine and loaded progressively until failure. The maximum load was recorded and used to determine the compressive strength of the specimen.

For a 150 mm × 150 mm loaded face, the cross-sectional area was 22,500 mm². The compressive-strength results obtained from the replicate specimens were averaged to represent the compressive strength for each experimental condition.

TABLE II.

EXPERIMENTAL MATRIX FOR COMPRESSIVE STRENGTH TESTING

Age (day)	M0 (0%)		M3 (3%)		M5 (5%)		Total
	Water Curing	Soil Curing	Water Curing	Soil Curing	Water Curing	Soil Curing	
7 day	3	3	3	3	3	3	18
14 day	3	3	3	3	3	3	18
28 day	3	3	3	3	3	3	18
Total	9	9	9	9	9	9	54 cubes

F. Microstructural Analysis

Scanning Electron Microscopy (SEM) was employed to examine the microstructural features within the crack region following the designated healing period. The observations focused on changes in surface morphology, the extent to which crack spaces were occupied by newly formed deposits, and other features that could be associated with the microbial healing process. SEM examination has been widely applied in microbial self-healing concrete studies to provide supporting evidence of morphological changes and the development of healing products within the cementitious matrix [3], [5].

In the present study, SEM examination was conducted on selected M3 specimens subjected to water and soil curing at Days 7 and 28. The analysis focused on differences in crack-region morphology and the appearance of newly formed deposits over the curing period. Particular attention was given to whether the microstructural features observed under the two curing environments were consistent with the corresponding crack-healing behaviour. As SEM primarily provides morphological information, the observed deposits were interpreted as healing-related mineral precipitates rather than being conclusively identified as calcium carbonate ($CaCO_3$). Confirmation of their elemental or mineralogical composition would require complementary techniques such as EDS/EDX, XRD or FTIR.

G. Data Analysis

Quantitative results obtained from the replicate specimens were summarised using the average value for each experimental condition. For the compressive-strength assessment, the results of M0, M3 and M5 were compared at 7, 14 and 28 days to examine variations associated with concrete age, microbial-agent dosage and curing environment. Self-healing response was assessed by comparing changes in visible crack condition from the initial observation at Day 1 to subsequent observations at Days 14 and 28. Comparisons were made between M0 and M3 under water and soil curing conditions to examine whether microbial-agent incorporation and curing environment were associated with differences in crack-healing progression. M5 was excluded from the self-healing comparison because the specimens were damaged during demoulding as a result of insufficient early-age hardening

SEM observations of the selected M3 specimens were interpreted alongside the corresponding crack-healing results to provide complementary microstructural evidence. Particular attention was given to changes in crack-region morphology and the presence of healing-related deposits under water and soil curing conditions.

IV. RESULTS AND DISCUSSION

A.Compressive Strength Performance under Different Microbial Dosages and Curing Conditions

The compressive strength results presented in Table III demonstrate a consistent increase in strength with curing age across all mixtures. The control concrete developed comparable strength under both curing conditions, reaching 40.12 MPa in water and 39.89 MPa in soil at 28 days. A similar response was observed for the M3 mixture under water curing, which achieved 40.25 MPa. In contrast, M3 subjected to soil curing exhibited a more pronounced strength development, increasing from 28.91 MPa at Day 7 to 36.27 MPa at Day 14 and reaching 45.30 MPa at Day 28. This was the highest strength recorded among the investigated mixtures and represented an improvement of approximately 13.6% over the corresponding soil-cured control.

Increasing the microbial-agent content to 5 wt.% did not produce a similar improvement. Although strength continued to develop with curing age, the M5 specimens reached only 27.82 MPa under water curing and 30.34 MPa under soil curing at Day 28, corresponding to reductions of approximately 30.7% and 23.9%, respectively, relative to their corresponding controls. The results therefore indicate that the mechanical response was dependent on both microbial-agent dosage and curing environment rather than increasing proportionally with microbial content. Among the conditions investigated, the combination of 3 wt.% microbial agent and soil curing produced the most favourable compressive-strength performance. The suitability of this formulation for the Eco2GC Drain Cover, however, should be considered together with its crack-healing behaviour and microstructural characteristics.

TABLE III

COMPRESSIVE STRENGTH OF ECO2GC CONCRETE UNDER DIFFERENT MICROBIAL DOSAGES AND CURING CONDITIONS

Sample	Day 7	Day 14	Day 28
M0-W Control Sample (water curing)	27.33 MPa	34.50 MPa	40.12 MPa
M0-S Control Sample (soil curing)	27.95 MPa	34.72 MPa	39.89 MPa
M3-W Sample 3wt. % microbial agent (water curing)	27.23 MPa	33.97 MPa	40.25 MPa
M3-S Sample 3wt. % microbial agent curing)	28.91 MPa	36.27 MPa	45.30 MPa
M5-W Sample 5wt. % microbial agent (water curing)	21.67 MPa	23.01 MPa	27.82 MPa
M5-S Sample 5wt. % microbial agent (soil curing)	25.24 MPa	27.38 MPa	30.34 MPa

B. Self-Healing Performance under Water and Soil Curing

Visual crack-healing assessment was conducted on the M0 and M3 specimens under water and soil curing conditions over a 28-day observation period. Although M5 specimens were initially prepared for the same assessment, they had not developed sufficient hardness at the time of demoulding and were damaged during removal from the moulds. Consequently, meaningful crack-healing observations could not be obtained for this mixture, and the subsequent visual assessment focused on four conditions: M0-W, M0-S, M3-W and M3-S.

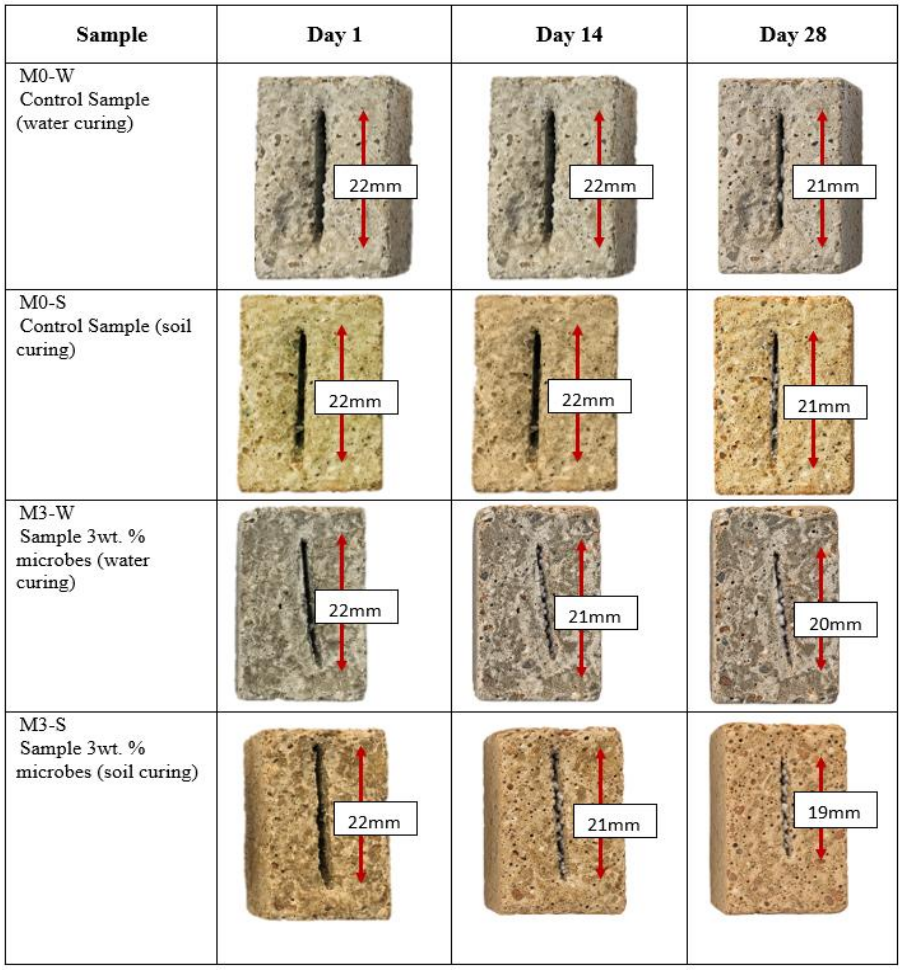


Fig. 2. Visual comparison of crack-healing progression in M0 and M3 specimens under water and soil curing conditions from Day 1 to Day 28.

As shown in Fig. 2, the initial visible crack length was approximately 22 mm for all evaluated specimens. The control specimens exhibited only minor changes during the 28-day observation period, with the visible crack length decreasing from 22 mm to 21 mm under both water and soil curing. In comparison, the M3 specimens showed a more progressive reduction. Under water curing, the visible crack length decreased from 22 mm at Day 1 to 21 mm at Day 14 and 20 mm at Day 28, whereas the soil-cured M3 specimen showed the greatest reduction, reaching 19 mm at Day 28. These observations indicate a more pronounced healing response in M3-S than in the corresponding control and water-cured microbial specimens.

Overall, the visual observations suggest that the combination of 3 wt.% Bacillus subtilis-based microbial agent and soil curing provided the most favourable condition for visible crack closure. The greater reduction in crack visibility observed for M3-S relative to M0-S also suggests that the response cannot be explained solely by the curing environment. Nevertheless, visual evidence alone is insufficient to confirm microbial-induced mineral precipitation. The observations should therefore be interpreted together with the subsequent microstructural analysis to determine whether the crack regions contain healing-related mineral deposits.

C. Microstructural Characteristics

SEM examination was conducted on selected M3 specimens under water and soil curing conditions at Days 7 and 28. As shown in Fig. 3, differences in surface morphology and the distribution of healing-related deposits became more apparent towards Day 28. Under water curing, the Day 28 specimen exhibited a greater presence of deposited material within the observed region compared with Day 7. A similar temporal change was evident under soil curing, where the Day 28 micrograph showed more pronounced material accumulation within and around the crack region.

The microstructural observations were consistent with the visual crack-healing assessment, in which M3-S exhibited the greatest reduction in visible crack length by Day 28. This correspondence suggests that the curing environment may have influenced the development of healing-related deposits within the cracked region. Nevertheless, the SEM images provide morphological rather than compositional evidence; therefore, the observed material cannot be conclusively identified as calcium carbonate without complementary EDS/EDX, XRD or FTIR analysis.

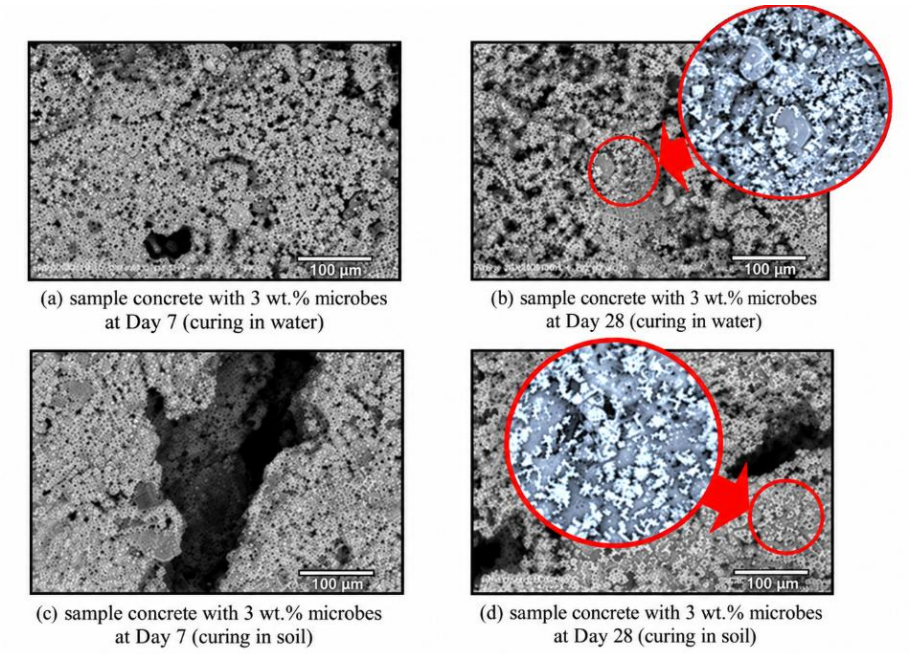


Fig. 3. SEM micrographs of M3 concrete specimens under (a) water curing at Day 7, (b) water curing at Day 28, (c) soil curing at Day 7, and (d) soil curing at Day 28 (×500 magnification).

D. Integrated Evaluation of Mechanical, Crack-Healing and Microstructural Performance

The combined results demonstrate that the performance of the microbial Eco2GC concrete was influenced by both microbial-agent dosage and curing environment. Among the mixtures investigated, M3 under soil curing exhibited the most favourable mechanical response, achieving a 28-day compressive strength of 45.30 MPa, compared with 40.25 MPa for the corresponding water-cured M3 specimen and 39.89 MPa for the soil-cured control. This represents an improvement of approximately 13.6% relative to M0-S. In contrast, increasing the microbial-agent dosage to 5 wt.% resulted in lower compressive strength, with M5-W and M5-S reaching only 27.82 MPa and 30.34 MPa, respectively, at Day 28. These findings indicate that increasing the microbial-agent content did not produce a proportional improvement in mechanical performance and that, under the conditions investigated, the 3 wt.% dosage provided a more favourable strength response.

The mechanical response of M3-S was also consistent with the visual crack-healing observations. The initial visible crack length of approximately 22 mm decreased to 19 mm at Day 28 under soil curing, compared with 20 mm for M3-W and 21 mm for both control specimens. Thus, the M3-S specimen exhibited the greatest reduction in visible crack length among the conditions successfully evaluated. The agreement between its comparatively high compressive strength and more pronounced crack reduction suggests that the combination of 3 wt.% microbial agent and soil curing provided the most favourable overall response. However, the increase in compressive strength should not be interpreted independently as evidence of microbial self-healing, since strength development may also be affected by cement hydration and curing conditions.

The SEM observations provide complementary microstructural evidence for interpreting the crack-healing response. Differences in surface morphology and the presence of healing-related deposits were observed between the water- and soil-cured M3 specimens, particularly towards Day 28. These microstructural features are considered alongside the greater visible crack reduction observed for M3-S, suggesting that the curing environment may have influenced the development of healing-related material within the crack region. Nevertheless, because SEM provides primarily morphological information, the observed deposits cannot be conclusively identified as calcium carbonate without complementary compositional or mineralogical analyses such as EDS/EDX, XRD or FTIR.

Overall, the combined mechanical, crack-healing and microstructural observations identify M3-S as the most promising condition among the successfully evaluated formulations. The findings also show that increasing the microbial-agent dosage beyond 3 wt.% did not necessarily improve performance, as the M5 mixture exhibited lower compressive strength and its self-healing specimens could not be meaningfully evaluated because of insufficient hardening during demoulding. Accordingly, the selection of microbial-agent dosage for further development of the Eco2GC Drain Cover should consider not only microbial content, but also its effects on early-age material stability, mechanical performance, crack-healing behaviour and the surrounding curing environment.

V. CONCLUSION

This study demonstrates that the performance of microbial concrete developed for the Eco2GC Drain Cover was influenced by both microbial-agent dosage and curing environment. Among the investigated mixtures, M3 under soil curing exhibited the most favourable mechanical performance, achieving a 28-day compressive strength of 45.30 MPa, approximately 13.6% higher than the corresponding soil-cured control. The same condition also showed the greatest reduction in visible crack length, decreasing from approximately 22 mm at Day 1 to 19 mm at Day 28. In comparison, the control specimens showed only a minor reduction to 21 mm, while M3 under water curing reached 20 mm.

Increasing the microbial-agent dosage to 5 wt.% did not improve mechanical performance, with M5-W and M5-S reaching 27.82 MPa and 30.34 MPa, respectively, at Day 28. In addition, the M5 specimens prepared for crack-healing assessment did not develop sufficient hardness for successful demoulding, preventing meaningful evaluation of their healing behaviour. SEM examination of M3 specimens provided complementary morphological evidence of healing-related deposits within the crack regions, although their composition could not be conclusively identified from SEM alone. Overall, the combined mechanical, visual and microstructural observations indicate that 3 wt.% microbial-agent incorporation combined with soil curing provided the most favourable overall response among the successfully evaluated conditions. Further investigation using quantitative crack-width measurements and complementary characterisation techniques such as EDS/EDX, XRD or FTIR is recommended to verify the composition of the healing products and strengthen the assessment of microbial-assisted crack repair.

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DECLARATION OF GENERATIVE AI USAGE

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to support language refinement, grammatical correction and the organisation of written content. The generated output was subsequently reviewed, revised and verified by the authors to ensure its accuracy and suitability for the manuscript. The authors take full responsibility for the final content of the article.

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