SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Micro and Nano Engineering

Journal homepage: https://semarakilmu.com.my/journals/index.php/micro_nano_engineering/index
ISSN: 2756-8210

Microbial Use as an Agent to Improve the Durability of Sub-Structure Concrete: A Comprehensive Structured Review

Affidah Mardziah Mukhtar[1,*], Julie Juliewatty Mohamed[2], Noor Azlina Ibrahim[2], Teo Pao Ter[2], Omar Hamza[3]

[1] Civil Engineering Department, Polytechnic of Kota Bharu, Km24 Pangkal Kalong, 16450 Ketereh, Kelantan, Malaysia
[2] Faculty of Bioengineering and Technology, Jeli Campus, University Malaysia Kelantan, 17600 Jeli, Kelantan, Malaysia
[3] College of Science and Engineering, University of Derby, Kedleston Road DE22 1GB, Derby, United Kingdom

ARTICLE INFO

Article history:
Received 6 August 2024
Received in revised form 19 September 2024
Accepted 28 October 2024
Available online 30 November 2024

Keywords:
Microbial; durability; substructure; concrete

ABSTRACT

The increasing degradation of sub-structure concrete due to environmental factors and aging has intensified the need for innovative and sustainable solutions to enhance its durability. To increase the longevity of sub-structure concrete, microbial use is becoming more and more important. One key technique in this exploration of the literature is Microbial-Induced Calcium Carbonate Precipitation (MICP). We reviewed over 50 peer-reviewed journal articles and conference papers published between 2020 and 2024, selecting those that specifically address microbial applications in concrete. To achieve this, we conducted an extensive search of scholarly articles from reportable databases, such as Scopus, IEE, and Science Direct, focusing on studies from 2020 to 2024. The flow of studies is based on the PRISMA framework. Our methodology involved analyzing the effectiveness of microbial treatments in extending the service life of concrete through qualitative and quantitative data synthesis. The studies found that n=29 final primary data was analyzed. The finding was divided into three themes, which are (1) Microbial Applications in Soil and Foundation Crack Stabilization, (2) Microbial Applications in Concrete and Construction Materials and (3) Advanced Microbial Technologies and their Impacts. Additionally, this study demonstrates the environmental sustainability of microbial applications compared to traditional chemical-based methods. The review concludes that while using microbes in concrete shows significant potential for enhancing durability and sustainability, further research is required to optimize these biological processes for mainstream construction practices and assess long-term of their impacts. This study lays the groundwork for future investigations into scalable microbial solutions, aiming to revolutionize the construction industry's approach to prolonging the lifespan of concrete infrastructures.

1. Introduction

Aspects of versatility, strength, as well as durability make concrete the most utilized construction material in the world. Sub-structure concrete, which forms foundations and other below-ground elements of structures, is particularly susceptible to many of these harmful processes. These

* *Corresponding author.*
E-mail address: affidah@pkb.edu.my

https://doi.org/10.37934/armne.26.1.111124

processes (chemical attack, physical wear, and biological influences) decrease the lifespan in addition to the integrity of concrete by a significant amount [1,2]. Usually, improved durability of concrete was sought after through means of material composition and protection against external agents utilizing sealants or coatings [3-5]. Fortunately, new advances in microbiology have come up with novel ways to tackle such problems using microbial technology in a sustainable manner.

Microbial-Induced Calcium Carbonate Precipitation (MICP) is an area of increasing prominence, which exploits the natural metabolic activity of certain strains of bacteria to improve the durability of concrete. These biogenic methodologies include the addition of ureolytic or non-ureolytic bacteria into the concrete matrix. These bacteria promote the precipitation of calcium carbonate ($CaCO_3$) in the concrete pores and cracks, thereby self-healing the concrete. The $CaCO_3$ crystals not only block the micro-cracks and voids but also enhance the density and impermeability of concrete, which increases the concrete's resistance to different environmental aggressors [6-8].

Bacteria utilization is intended to increase the durability of concrete. The idea of employing bacteria to help improve the durability of concrete is based on a natural process called biomineralization, in which living organisms produce minerals. It is especially effective in hostile settings, where conventional repair techniques are either non-feasible or ineffective. Bacteria commonly used in MICP, such as Sporosarcina pasteurii grow in an alkaline environment and are capable of precipitating large quantities of $CaCO_3$ [9,10]. Due to this, precipitated $CaCO_3$ binds the aggregates and cement matrix more effectively, which results in reducing porosity and increases the compressive strength.

Many investigations have reported that MICP can strengthen the durability of concrete. Both laboratory experiments and field trials have demonstrated that water permeability reduction, crack remediation, as well as resistance to freeze-thaw cycles are superior in bacterial-treated concrete beds. Bacterial-treated samples have been shown to reduce the water permeability by as much as 90% when compared to the untreated samples [11,12]. Referring to Figure 1 [13], principles as well as processes with regards to MICP technology for crack healing can be shown. Furthermore, the self-healing capacity of the bacteria-based concrete can increase the lifespan of sub-structures and, hence, reduce the maintenance cost and environmental effect caused by frequent repair.

Microbial technology and sustainable construction practices also fit together regarding the use of microbial technology in concrete. Concrete usage is widely utilized, and conventional methods of concrete, as well as repair methods, substantially increase carbon footprint in addition to environmental degradation [14,15]. Microbial applications, on the contrary, employ naturally occurring processes, consuming minimal energy input as well as resulting in lower pollutant forms. In addition to improved durability, the employment of bacteria in concrete also encourages a sustainable method of construction, which in turn helps decrease the carbon footprint of the construction industry.

Although microbial technology in concrete could have a very promising future, a few hindrances and issues need to be considered and must be addressed to make it utilized everywhere. This includes optimizing bacterial strains to perform under a variety of possible environmental conditions, ensuring bacterial survival and long-term activity inside the concrete matrix as well as developing practical and low-cost methods of application [16,17]. Additional research is therefore required to develop a comprehensive understanding of the interactions between microbial activity and concrete properties and to improve the methods used to incorporate bacteria into the concrete mix and during curing.

Finally, one of the important technical advancements in the area of concrete durability is the application of microbial technology. Using the natural bacteria-based processes to precipitate $CaCO_3$, the structural integrity as well as the longevity of the sub-structure concrete can be improved. It is believed to be one very new type of sustainable solution to the ongoing problem of concrete deterioration, and it opens further implications for construction materials research and development. With this ongoing effort from the construction industry to build for resiliency and eco-friendly elements, microbial technology appears to be a uniquely attractive technology.

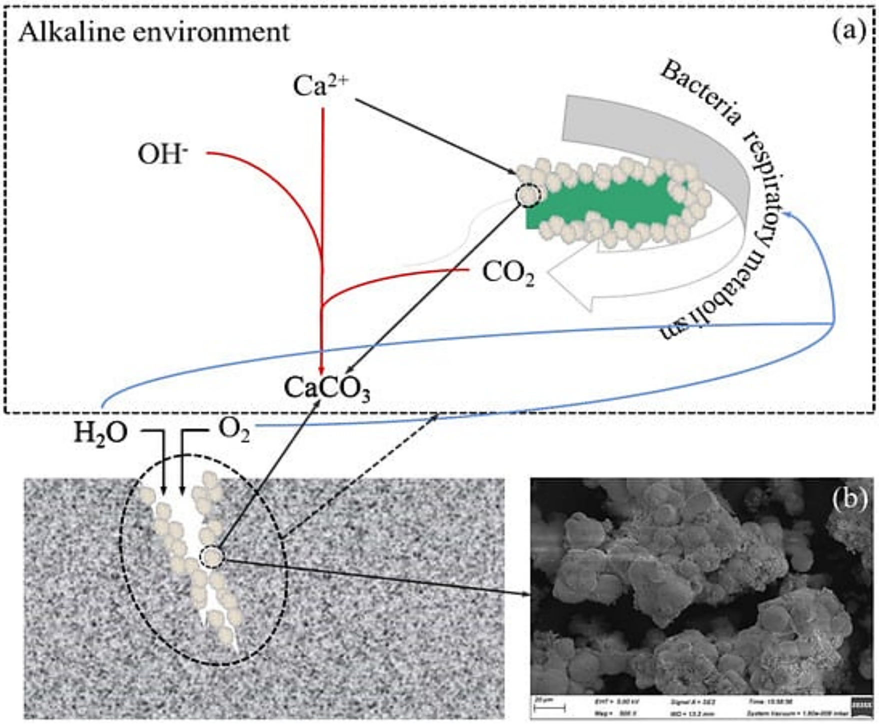

Fig. 1. Principles as well as processes with regards to MICP technology for crack healing (a) Microbially induced $CaCO_3$ crack in cement-based material (b) Morphology of microbial-induced calcite [13]

2. Literature Review

MICP is a newly developed technology to improve the durability of concrete structures, especially in sub-structure applications where durability is a challenging issue. As can be seen from the works of Molyneux [18] as well as De Belie [19], some specific microbial treatments on concrete can markedly improve the physical properties by encouraging $CaCO_3$ formation, which seals cracks effectively and makes concrete much less permeable. Because of their ability to increase the longevity of concrete structures exposed to aggressive environmental conditions, this technique has been widely investigated.

Giroudon *et al.,* [20] discovered that alkali-activated metakaolin and calcium aluminate cement showed significantly greater resistance than Portland cement when they were investigating the performance of low CO_2 binders pertaining to biogas structures. These results demonstrate the promise of improved microbial treatments produced by alternative binders to improve concrete durability in aggressive environments. Likewise, Zhang *et al.,* [21] discovered that the sodium alginate-aided bio-deposition technique was utilized to enhance the uniformity as well as efficiency of the microbial treatment on recycled aggregates, in which there was a substantial decrease in water absorption and an increase in compressive strength. It is concluded by these studies that the variation of application methods and binder compositions should be considered for more durable concrete structures.

Wei *et al.,* [22] studied repairing the high-temperature-damaged concrete by MICP [21]. They discovered that calcium acetate is an effective calcium resource for microbial mineralization. In general, the work demonstrated that when MICP is employed, it leads to an enhancement in compressive strength and a decrease in water absorption, mainly at higher temperatures. It further suggests the effectiveness of the MICP despite differences in conditions. In addition, Sivamani [23] observed the self-healing behaviour of Bacillus subtilis as well as Escherichia coli-based concrete and remarked on the better role of B. subtilis compared to E. coli in aiding the development of mechanical and durability properties. These results shed light on the necessity to choose appropriate bacterial strains for targeted applications in order to tap the full potential of MICP.

Serrano-González *et al.,* [24] indicated that biotreatments with microbial mixed cultures with crude glycerol and waste pinewood revealed improved durability of recycled concretes. These treatments reduced water penetration, which therefore prolonged the lifespan of the concrete, demonstrating the opportunity to use microbiological treatments with sustainable materials. Bhattacharyya *et al.,* [25] concentrated on fungal biodeterioration; nanosilica coatings were proved to be very effective in preventing any fungal growth, thus increasing the durability of concrete. This reinforces how crucial it is to incorporate microbiological and nanotechnological processes in an all-round concrete preservation.

Chen and Lin [26] studied the self-healing ability of the bacterium-based concrete and reported that Sporosarcina pasteurii had a better self-healing effect than B. subtilis. The research results showed major improvements in compressive strength and water resistance, laying the foundation for the use of microbial agents to fill cracks and improve the performance of concrete. Meanwhile, Mi *et al.,* [27] explored the techniques for improving the properties of the recycled brick aggregate by applying MICP and Enzyme-Induced Carbonate Precipitation (EICP). Both of those treatments led to a better performance of recycled brick aggregate, and the EICP treatment was able to show a better performance since it has a uniform precipitation distribution of the treatments.

Su and Jin [28] investigated the utilization of encapsulated expanded vermiculites as microorganism carriers in self-repairing concrete. They were able to state that this approach can substantially increase the durability and self-healing potential of concrete structures. According to the study, the appropriate carriers are essential for the effectiveness of metabolic treatments in concrete. An extensive study on microbial self-healing concrete was proposed by Yip *et al.,* [29] with reference to the work on bacterial self-healing concrete and the requirements of further investigation into the bacterial viability and immobilization methods to promote the practical applications of this technology. The process pertaining to self-healing as depicted in Figure 2 [30].

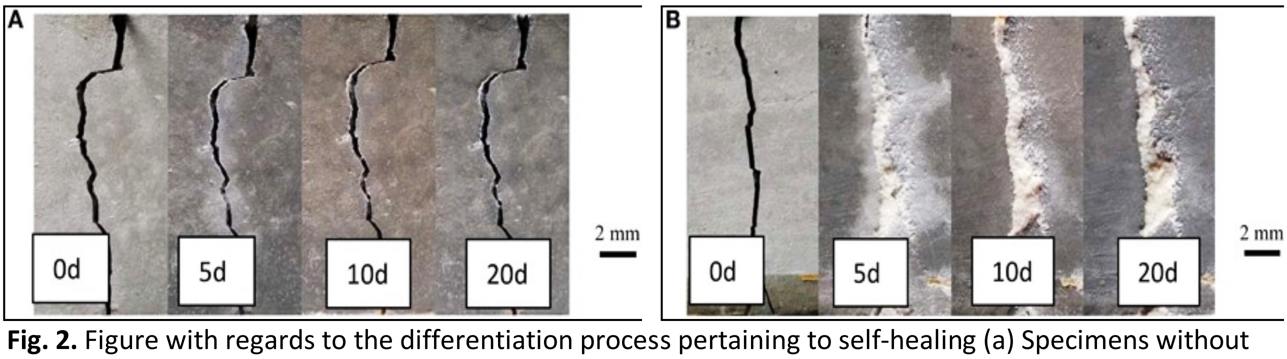

Fig. 2. Figure with regards to the differentiation process pertaining to self-healing (a) Specimens without self-healing (b) Specimens with self-healing agent [30]

Deverajan and Sivamani [31] investigated the impact of bio-deposited recycled aggregates on concrete properties, showing that microbial treatments significantly improved the strength and durability of recycled aggregate concrete. This research highlights the potential of microbial techniques to enhance the performance of sustainable construction materials. Iranfar *et al.,* [32] reviewed the prioritization of construction materials for habitat construction on Mars, finding that microbial-induced calcite precipitation is among the most efficient methods for concrete durability under extreme conditions. Furthermore, [33] claimed that creating green concept building materials will have numerous advantages, particularly in terms of protecting the surrounding environment. This study indicates the potential of MICP for future space construction applications.

The combined insights from these studies illustrate the significant contributions of microbial use to enhancing the durability of sub-structure concrete. By optimizing microbial treatments, binder compositions, and application methods, it is possible to develop more durable, sustainable, and resilient concrete structures.

3. Methodology
3.1 Identification

Three fundamental stages of the systematic review procedure were employed to choose many pertinent publications for this investigation. In the first stage, keywords are chosen, and similar terms are looked for utilizing thesaurus, dictionaries, encyclopedias, and previous research. Following the creation of search strings for the Scopus and IEE databases (see Table 1), all applicable keywords were chosen. Note that 127 publications from both databases were successfully obtained for the present study project during the initial phase of the systematic review procedure.

Table 1
The search string

Scopus	TITLE-ABS-KEY ((microbial OR microbe) AND (durability OR strength) AND ("sub-structure concrete" OR foundation)) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2024)) Date of access: 26 Mei 2024.
IEE	(microbial OR microbe) AND (durability OR strength) AND (sub-structure concrete" OR foundation) Date of access: 26 Mei 2024.

3.2 Screening

The collection of possibly relevant research items is screened to make sure its content fits the selected study topic or questions. During the screening stage, content-related criteria are frequently applied. For example, research articles are chosen using Microbial Use as An Agent to Improve the Durability of Sub-Structure Concrete. From the list of papers that were searched in this stage, all duplicate papers will be removed. Following the exclusion of 93 articles in the first screening stage, 37 papers were assessed in the second screening stage using a variety of inclusion and exclusion criteria from this inquiry (see Table 2). Before applying any other criterion, this one was chosen because research publications are the primary source of helpful advice. Reviews, meta-synthesis, meta-analyses, books, book series, chapters, and conference proceedings are not included in the most recent study. Furthermore, only English-language articles were included in the review. It is crucial to remember that the plan was only applicable from 2020 to 2024. Twenty papers in all were rejected because of duplicate criteria.

Table 2
The selection criterion is searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Timeline	2020-2024	< 2020
Literature type	Journal (article)	Conference, book, review
Publication stage	Final	In press
Subject	Environmental Science	Others Environmental Science

3.3 Eligibility

When every requirement for inclusion and exclusion has been satisfied, the final review sample is produced. Since readers would not be able to determine which specific research items serve as the basis for the review's study results without comprehensive disclosure of the entire list of research items contained in this sample, it is necessary. The third level, known as eligibility, consists of 73 articles altogether. At this stage, every article title and important passage was thoroughly examined to make sure the inclusion criteria were satisfied and the articles were pertinent to the research goal of the current study. Here, 48 publications were consequently eliminated since, based on facts, their title and abstracts had no discernible bearing on the goal of the study. Ultimately, a total of 25 papers were provided for assessment.

3.4 Data Abstraction and Analysis

An integrative analysis, which examined and synthesized a variety of research designs (qualitative, mixed, and quantitative), was one of the assessment techniques in this study. The competence study aimed to identify relevant topics and subtopics. The data collection phase was the first stage of the theme's development. Figure 3 illustrates the method by which the writers meticulously reviewed a collection of 25 publications to look for assertions or details relevant to the topics of the current study. The authors then evaluated the significant recent studies on microorganism classification. The research findings and the methodologies used in each study are the subject of investigation. The author then collaborated with the other co-authors to develop themes derived from the study's background data. A log was kept during the data analysis process to document observations, thoughts, conundrums, and other ideas relevant to the interpretation of the data. Finally, the writers reviewed the results to see whether there was any consistency in the theme design process. It is crucial to remember that the writers discuss any disagreements regarding the concepts with one another. In the end, coherence was ensured by adjusting the developed themes. The analysis selection in Microbiology and Engineering Science & Technology was done by two experts. The following is the research question:

i. How do various microbial treatments enhance the mechanical properties, stability, and durability of different types of soils and foundation materials?
ii. What are the effects of microbial applications on the durability and self-healing capabilities of concrete and construction materials under various environmental conditions?
iii. How can advanced microbial technologies be optimized for microbial technologies and their impacts?

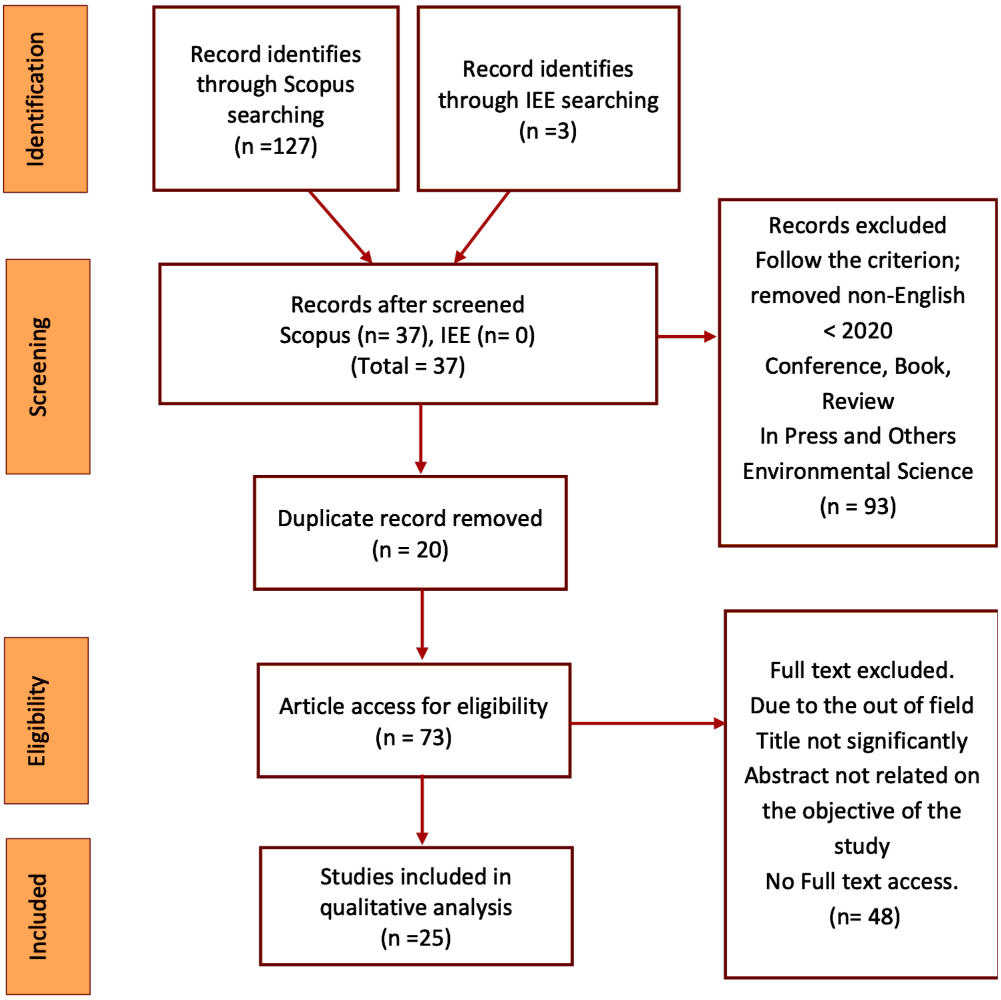

Fig. 3. Flow diagram of the proposed searching study

4. Results

4.1 Applications in Soil and Foundation Crack Stabilization

MICP is increasingly recognized as a sustainable technique for improving soil stability and enhancing the mechanical properties of various soil types. Khodabandeh *et al.,* [34] extensively explore the versatility of MICP alongside other materials, such as nanomaterials, fibres, and industrial wastes, to stabilize collapsible soils. This method significantly enhances the soil's mechanical attributes, such as shear strength and compressive strength. Similar enhancements are noted by Lin *et al.,* [35], who details the use of basalt fibres in conjunction with biocement to reinforce calcareous sand, improving both tensile strength and the soil's overall structural integrity.

Shan *et al.,* [36] and Han *et al.,* [37] focus on the application of MICP in enhancing liquefaction resistance in calcareous sands and saturated sands, respectively. Their research demonstrates that MICP not only solidifies the soil matrix but also provides the best distribution of the main component, $CaCO_3$. This is beneficial for improving soil's performance in mitigating earthquake-induced soil liquefaction. This efficacy is also reflected in the results of Sun *et al.,* [38]. It is noteworthy that the significant potential of MICP treatment to improve the liquefaction resistance of loess engineering soils was observed, which is required to ensure the stability of large-scale infrastructures.

Moreover, Naskar *et al.,* [39] show how MICP can lead to economic savings and environmental adaptability in lateritic soils, usually composing an important part of the infrastructures. Soil

Unconfined Compressive Strength (UCS) shows a significant compression improvement after amending with some biogenic calcite and magnetite nanoparticles, indicating the same ecological benefits of conventional soil stabilization processes without the need for any additional chemicals that may be harmful.

Wang *et al.,* [40], as well as Hu *et al.,* [41], address the issue of the decrease in soil, which is commonly found in biocementation. By altering the microbial strains applied in MICP, they used this modification to improve the brittleness of biocemented soils and their durability and mechanics under stress. The advantage of this development would be that it may promote the spreading of MICP in geotechnical applications.

Microbial methodologies are not only used to stabilize soil but have also been reimagined to solve particular environmental concerns. For instance, Liu *et al.,* [42] utilize an industrial waste product (sintering red mud) in a project that tackles such waste as a rich source of strategic material; the mineralization by a microbial activity has already been implemented where the waste would be converted to building material. This landfilling-free process not only helps in waste management but also minimizes any detrimental effect on the environment when disposing of red mud.

Research by Hu *et al.,* [43] as well as Zamani *et al.,* [44] further indicate the capacity of MICP to increase soil strength and reduce liquefaction risk, which collectively elucidates the vast potential of MICP. The implications of these results point towards the profound effect of microbial technologies on civil engineering in the future in making the built environment resilient and sustainable.

The application of microbially induced calcium carbonate precipitation (MICP) for stabilising soil and foundation cracks has improved the mechanical characteristics and longevity of sub-structure concrete. It has been demonstrated that combining MICP with fibres, nanomaterials, and industrial wastes improves the compressive, tensile, and shear strengths of the soil. Furthermore, MICP has shown successful in boosting soil types' resistance to liquefaction, which is essential for the stability of large-scale infrastructures. By strengthening soil strength without the use of hazardous chemicals, this technique also has positive effects on the environment and the economy. In biocemented soils, durability and brittleness have been studied further, encouraging the use of MICP in geotechnical domains and in conjunction with industrial waste to produce sustainable building materials.

4.2 Microbial Applications in Concrete and Construction Materials

Microbial applications in concrete and construction materials have emerged as innovative and eco-friendly solutions for enhancing the durability and self-healing capabilities of construction materials. Recent research highlights various microbial techniques that significantly contribute to developing and maintaining sustainable infrastructure. Below are Table 3 that show the research article's findings based on “Microbial applications in concrete and construction materials”.

Table 3
The research article's findings based on microbial applications in concrete and construction materials

No.	Author name and year	Objectives	Methodologies	Findings	Conclusion and future research
1	Elam and Björdal, 2020 [45]	Evaluate factors affecting the stability of wooden foundation piles in urban construction environments.	Review and case studies	Urban construction work changes soil biogeochemistry, increasing microbial decay of wood piles, which causes damage.	Further study on soil types, groundwater levels, and hydrogeological matrix is suggested to enhance preventive measures.
2	Sun and Miao, 2020 [38]	Explore the application of MICP for crack repair in concrete at low temperatures.	Experimental tests using Bacillus megaterium	MICP effectively seals cracks at low temperatures, with variations in effectiveness based on microbial strain and nutrient additions.	Encourages future research on optimizing microbial strains and conditions for enhanced repair efficacy.
3	Amjad *et al.,* 2023 [46]	Investigate self-healing capabilities in concrete using Sporosarcina aquimarina in expanded perlite.	Comparative experiments with different self-healing techniques	Effective self-healing of concrete cracks with microbial techniques, showing superior results over direct bacterial addition.	Suggests further exploration of microbial carriers and their scaling up for widespread construction use.
4	Zamani *et al.,* 2021 [44]	Assess the efficacy of MICP treatment to reduce soil liquefaction effects under building foundations.	Centrifuge testing at UC Davis	MICP treatment significantly reduced settlements induced by soil liquefaction.	Calls for further investigation into the system-level performance of MICP-treated foundations under varied conditions.
5	Li *et al.,* 2022 [47]	Develop an eco-friendly MICP method for protecting monopile foundations from scour.	Scour tests in a large section flume	MICP significantly reduces scour depth around monopile foundations, enhancing stability.	Future research should address the balance of MICP protection times and manage edge scour effects.
6	Boob *et al.,* 2024 [48]	Improve pathway design for microbial production of valuable molecules using machine learning.	Multiplex experimentation and machine learning	Demonstrated the potential of machine learning to enhance the efficiency of microbial production pathways.	Advocates for further exploration of machine learning to optimize microbial pathways for industrial applications.

4.3 Advanced Microbial Technologies and Their Impacts

In sub-structure applications where durability is a major concern, microbially induced calcium carbonate precipitation, or MIP, has shown promise as a method to improve the durability of concrete structures. Through the successful sealing of cracks and reduction of permeability caused by the deposition of calcium carbonate, a variety of microbial treatments have demonstrated significant benefits in the characteristics of concrete. By raising extracellular pH, Hoffmann *et al.,* [49] showed that genetic modification of Bacillus subtilis for MICP greatly improves biomineralization.

According to Bandyopadhyay *et al.,* [50], MICP is a sustainable way to increase the durability of concrete while lowering greenhouse gas emissions because it can both repair concrete fractures and capture CO_2.

Tan *et al.,* [51] conducted a thorough evaluation of the impact of biomineralization on the microstructure and durability of concrete. They discovered that MICP alters the phase assemblages close to healed fissures and increases the durability of cementitious composites. In their review of microbial carbonate precipitation through the denitrification process, Jain *et al.,* [52] emphasised the advantages of this pathway over alternative ones as well as its possible uses in construction materials, such as bio concrete and soil reinforcement. High rates of crack closure and water permeability restoration were seen in Li *et al.,* [53] study of the biomineralization process brought on by Bacillus mucilaginous, demonstrating the efficacy of MICP in self-healing concrete.

The durability of recycled concrete was shown to be significantly improved by Serrano-González *et al.,* [24] research from 2023 on eco-friendly biotreatments employing microbial mixed cultures with crude glycerol and waste pinewood, which also reduced water penetration and increased longevity. In their study of fungal biodeterioration, Bhattacharyya *et al.,* [25] shown how well fungal growth is inhibited and concrete durability is increased by nanosilica coatings.

In their investigation of the use of MICP to stop Pb2+ migration in soil profiles, Song *et al.,* [54] showed that MICP successfully immobilises lead, lowering its movement and emphasising the wider environmental uses of MICP. In their study of the use of MICP in soil solidification and heavy metal stabilisation, Xu and Wang [55] emphasised the mechanisms of biosorption and biomineralization as well as the technology's potential to enhance soil qualities and stabilise heavy metals. In their thorough analysis of MICP technology for concrete crack repair, Zhang *et al.,* [56] covered the technology's self-healing properties as well as the technical difficulties encountered in intricate engineering situations.

5. Discussion and Conclusions

MICP is a sustainable approach that can improve the stability of soil and mechanical properties. This can be used alone, as well as in conjunction with other materials, to aim for the stabilization of collapsible soil, reinforcement of calcareous sand, increase of liquefaction resistance, as well as reduction of soil brittleness. This novel biotechnology could also be useful in various fields, including waste management and environmental sustainability. Hence, microbial technology provides an enormous paradigm shift in civil engineering, increasing the resilience and sustainability of built environments.

Accommodation of state-of-the-art microbial technologies in concrete and construction materials has profound implications on an even wider array of infrastructure sustainability and durability. Research in different application areas shows the potential for a reduction in environmental impact and an improvement of material properties. To illustrate, it was demonstrated that MICP could seal cracks in concrete at low temperatures while also reducing soil liquefaction under building foundations, which highlights the importance of selecting the best microbial and optimized treatment conditions. Sporosarcina aquimarina, as utilized here in self-healing concrete, is a new concept that might be the start for widespread use within the industry.

This study additionally sheds new light on the comprehension of environmental factors, for instance, soil types as well as hydrogeological conditions to keep microbial decay from taking hold in wooden foundation piles. Furthermore, the application of sustainable MICP methods is able to contribute to the practical use of microbial technologies for improved stability of marine structures. Together, these studies highlight a departure from exploiting microbial phenomena solely for improved material properties to also considering microbial contributions to low environmental impact, supporting ongoing research and industrial implementation.

The collective knowledge gained from these investigations shows how important microbial utilisation is in improving the longevity of sub-structure concrete. Concrete constructions can be made more robust, resilient, and sustainable by maximising microbiological treatments, binder formulations, and application techniques. The study highlights the potential of MICP in environmental remediation, sustainable construction methods, and concrete rehabilitation.

Acknowledgement
This research was not funded by any grant.

References

[1] Kokas, Balázs, Jeno Balogh, Agnes Borsos, Gabriella Medvegy, and Bálint Bachmann. "Harmonization of structural and functional lifespans of prefabricated residential buildings." *International Journal of Design & Nature and Ecodynamics* 15, no. 2 (2020): 161-165. https://doi.org/10.18280/ijdne.150204

[2] Udhaya, S., V. Vandhana Devi, J. Philips, and R. L. Lija. "Experimental study on bio-concrete for sustainable construction." *Materials Today: Proceedings* (2023). https://doi.org/10.1016/j.matpr.2023.03.676

[3] Nodehi, Mehrab, Togay Ozbakkaloglu, and Aliakbar Gholampour. "A systematic review of bacteria-based self-healing concrete: Biomineralization, mechanical, and durability properties." *Journal of Building Engineering* 49 (2022): 104038. https://doi.org/10.1016/j.jobe.2022.104038

[4] Creasey, R., J. P. Andrews, S. O. Ekolu, and D. Kruger. "Long-term 20-year performance of surface coating repairs applied to façades of reinforced concrete buildings." *Case Studies in Construction Materials* 7 (2017): 348-360. https://doi.org/10.1016/j.cscm.2017.11.001

[5] Hill, David. "Self-healing concrete uses bacteria to repair cracks." *Civil Engineering Magazine Archive* 85, no. 7 (2015): 44-45. https://doi.org/10.1061/ciegag.0001016

[6] Nair, Priya S., Rajesh Gupta, Vinay Agrawal, and Blessen S. Thomas. "A critical review on the effectiveness of microbial concentrations for enhancing self-healing in cement concrete and mortar." *Materials Today: Proceedings* (2023). https://doi.org/10.1016/j.matpr.2023.03.546

[7] Cao, Mingli, Mehran Khan, and Shakeel Ahmed. "Effectiveness of calcium carbonate whisker in cementitious composites." *Periodica Polytechnica Civil Engineering* 64, no. 1 (2020): 265-275. https://doi.org/10.3311/PPci.14288

[8] Van Tittelboom, Kim, Nele De Belie, Willem De Muynck, and Willy Verstraete. "Use of bacteria to repair cracks in concrete." *Cement and Concrete Research* 40, no. 1 (2010): 157-166. https://doi.org/10.1016/j.cemconres.2009.08.025

[9] Wang, Yuze, Kenichi Soga, Jason T. DeJong, and Alexandre J. Kabla. "Effects of bacterial density on growth rate and characteristics of microbial-induced $CaCO_3$ precipitates: Particle-scale experimental study." *Journal of Geotechnical and Geoenvironmental Engineering* 147, no. 6 (2021): 04021036. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002509

[10] Wilcox, Samantha M., Catherine N. Mulligan, and Carmen Mihaela Neculita. "Microbially Induced Calcium Carbonate Precipitation as a Bioremediation Technique for Mining Waste." *Toxics* 12, no. 2 (2024): 107. https://doi.org/10.3390/toxics12020107

[11] Bisht, Vishakha, Leena Chaurasia, and L. P. Singh. "Studies on Corrosion and Carbonation Resistance by Bacteria-Mediated Mineralization in Concrete." *ACI Materials Journal* 117, no. 4 (2020). https://doi.org/10.14359/51724610

[12] Tursi, Antonio, Giovanni Brandimarte, GianMarco Giorgetti, and Gabriella Nasi. "Assessment of orocaecal transit time in different localization of Crohn's disease and its possible influence on clinical response to therapy." *European Journal Of Gastroenterology & Hepatology* 15, no. 1 (2003): 69-74. https://doi.org/10.1097/00042737-200301000-00012

[13] Feng, Chunhua, Xudong Zong, Buwen Cui, Hui Guo, Wenyan Zhang, and Jianping Zhu. "Application of carrier materials in self-healing cement-based materials based on microbial-induced mineralization." *Crystals* 12, no. 6 (2022): 797. https://doi.org/10.3390/cryst12060797

[14] Adikari, AM Priyangani, Haiyun Liu, D. M. S. L. B. Dissanayake, and Manjula Ranagalage. "Human capital and carbon emissions: the way forward reducing environmental degradation." *Sustainability* 15, no. 4 (2023): 2926. https://doi.org/10.3390/su15042926

[15] Ehigiamusoe, Kizito Uyi, Hooi Hooi Lean, Marina Mustapha, and Suresh Ramakrishnan. "Industrialization, globalization, ICT, and environmental degradation in Malaysia: A frequency domain analysis." *Heliyon* 9, no. 10 (2023). https://doi.org/10.1016/j.heliyon.2023.e20699

[16] Nery, Martín Eduardo Espitia, Dery Esmeralda Corredor Pulido, Paula Andrea Castaño Oliveros, Johan Andrey Rodriguez Medina, Querly Yubiana Ordoñez Bello, and Maikol Santiago Perez Fuentes. "Mechanisms of encapsulation of bacteria in self-healing concrete." *Dyna* 86, no. 210 (2019): 17-22. https://doi.org/10.15446/dyna.v86n210.75343

[17] Tang, Yihong, and Jing Xu. "Application of microbial precipitation in self-healing concrete: A review on the protection strategies for bacteria." *Construction and Building Materials* 306 (2021): 124950. https://doi.org/10.1016/j.conbuildmat.2021.124950

[18] Molyneux, Katie. "Bacterial concrete: a sustainable building material with advantageous properties." *Youth STEM Matters* 1, no. 1 (2020). https://doi.org/10.51892/ysm.1.202101

[19] De Belie, Nele. "Application of bacteria in concrete: a critical evaluation of the current status." *RILEM Technical Letters* 1 (2016): 56-61. https://doi.org/10.21809/rilemtechlett.2016.14

[20] Giroudon, Marie, Cédric Patapy, Matthieu Peyre Lavigne, Mialitiana Andriamiandroso, Robin Cartier, Simon Dubos, Céline Bacquié, Ludovic André, Sébastien Pommier, Xavier Lefevbre, Martin Cyr, and Alexandra Bertron. "Potential of low carbon materials facing biodeterioration in concrete biogas structures." *Materials and structures* 56, no. 4 (2023): 80. https://doi.org/10.1617/s11527-023-02174-0

[21] Zhang, Xuan, Changhao Fu, Qiwei Zhan, Yilin Su, Xiaojin Li, Yang Wu, Guangjin Xu, and Pengcheng Zhou. "Self-healing properties and improvement methods of mortar cracks in marine corrosive environments." *Journal of Building Engineering* 78 (2023): 107676. https://doi.org/10.1016/j.jobe.2023.107676

[22] Wei, Hong, Yanan Fan, Hongxiu Du, Renwang Liang, and Xiaoyuan Wang. "Regulation of Calcium Source and Addition Method for MICP in Repairing High-Temperature Concrete Damage." *Applied Sciences* 13, no. 9 (2023): 5528. https://doi.org/10.3390/app13095528

[23] Sivamani, Jagan. "Bio-remediation of cracks–a novel technique to self-heal cracks in the concrete." *European Journal of Environmental and Civil Engineering* 27, no. 14 (2023): 4086-4100. https://doi.org/10.1080/19648189.2023.2171140

[24] Serrano-González, Lorena, Daniel Merino-Maldonado, Andrea Antolín-Rodríguez, Paulo C. Lemos, Alice S. Pereira, Paulina Faria, Andrés Juan-Valdés, Julia García-González, and Julia Mª Morán-del Pozo. "Biotreatments Using Microbial Mixed Cultures with Crude Glycerol and Waste Pinewood as Carbon Sources: Influence of Application on the Durability of Recycled Concrete." *Materials* 15, no. 3 (2022): 1181. https://doi.org/10.3390/ma15031181

[25] Bhattacharyya, Subarna, Shaheen Akhtar, Anirban Chaudhuri, Shouvik Mahanty, Punarbasu Chaudhuri, and Mathummal Sudarshan. "Affirmative nanosilica mediated approach against fungal biodeterioration of concrete materials." *Case Studies in Construction Materials* 17 (2022): e01258. https://doi.org/10.1016/j.cscm.2022.e01258

[26] CHEN, Ming Ta, And Hui Yi LIN. "The Effect of Self-Healing Microorganism-Encapsulating Concrete on Enhancing Concrete Compressive Strength." *Materials Science* 29, no. 4 (2023): 474-480. https://doi.org/10.5755/j02.ms.33751

[27] Mi, Tangwei, Ligang Peng, Keqiong Yu, and Yuxi Zhao. "Enhancement strategies for recycled brick aggregate concrete using MICP and EICP treatments." *Journal of Building Engineering* 79 (2023): 107909. https://doi.org/10.1016/j.jobe.2023.107909

[28] Su, Yilin, and Peng Jin. "Application of encapsulated expanded vermiculites as carriers of microorganisms and nutrients in self-repairing concrete." *Biochemical Engineering Journal* 187 (2022): 108672. https://doi.org/10.1016/j.bej.2022.108672

[29] Yip, Bao Fang, Mohd Ridza Mohd Haniffah, Erwan Hafizi Kasiman, and Ahmad Razin Zainal Abidin. "Research progress on microbial self-healing concrete." *Jurnal Teknologi* 84, no. 3 (2022): 25-45. https://doi.org/10.11113/jurnalteknologi.v84.17895

[30] Qian, Chunxiang, Huaicheng Chen, Lifu Ren, and Mian Luo. "Self-healing of early age cracks in cement-based materials by mineralization of carbonic anhydrase microorganism." *Frontiers in microbiology* 6 (2015): 1225. https://doi.org/10.3389/fmicb.2015.01225

[31] Deverajan, Ambika, and Jagan Sivamani. "Influence of bio-deposited recycled aggregate on the concrete properties." *European Journal of Environmental and Civil Engineering* 28, no. 9 (2024): 2080-2098. https://doi.org/10.1080/19648189.2023.2293818

[32] Iranfar, Soha, Mohammad Mehdi Karbala, Mohammad Hossein Shahsavari, and Veerle Vandeginste. "Prioritization of habitat construction materials on Mars based on multi-criteria decision-making." *Journal of Building Engineering* 66 (2023): 105864. https://doi.org/10.1016/j.jobe.2023.105864

[33] Kassim, Umar, Said Nur, Wan Azani Wan Mustafa, and Mohd Nazaruddin Yusoff. "Green organic partition board from waste materials as soundproof material." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 30, no. 2 (2023): 304-313. https://doi.org/10.37934/araset.30.2.304313
[34] Khodabandeh, Mohammad Ali, Gábor Nagy, and Ákos Török. "Stabilization of collapsible soils with nanomaterials, fibers, polymers, industrial waste, and microbes: Current trends." *Construction and Building Materials* 368 (2023): 130463. https://doi.org/10.1016/j.conbuildmat.2023.130463
[35] Lin, Shengqiang, Xuewen Lei, Qingshan Meng, and Jianping Xu. "Properties of biocemented, basalt-fibre-reinforced calcareous sand." *Proceedings of the Institution of Civil Engineers-Ground Improvement* 176, no. 1 (2023): 14-22. https://doi.org/10.1680/jgrim.19.00023
[36] Shan, Yi, Jitong Zhao, Huawei Tong, Jie Yuan, Donglin Lei, and Yuanyuan Li. "Effects of activated carbon on liquefaction resistance of calcareous sand treated with microbially induced calcium carbonate precipitation." *Soil Dynamics and Earthquake Engineering* 161 (2022): 107419. https://doi.org/10.1016/j.soildyn.2022.107419
[37] Han, Zhiguang, Jianzhang Xiao, and Yingqi Wei. "Spatial distribution characteristics of microbial mineralization in saturated sand centrifuge shaking table test." *Materials* 15, no. 17 (2022): 6102. https://doi.org/10.3390/ma15176102
[38] Sun, Xiaohao, and Linchang Miao. "Application of bio-remediation with Bacillus megaterium for crack repair at low temperature." *Journal of Advanced Concrete Technology* 18, no. 5 (2020): 307-319. https://doi.org/10.3151/jact.18.307
[39] Naskar, Joyprakash, Subhadeep Chowdhury, Avishek Adhikary, Supriya Pal, and Sufia Khannam Kazy. "Strength enhancement of lateritic soil through mechanical mixing with magnetite nanoparticles, starch solution, and calcite precipitating bacteria." *Arabian Journal of Geosciences* 14, no. 18 (2021): 1901. https://doi.org/10.1007/s12517-021-08243-4
[40] Wang, Xiaorong, Chi Li, Wenhan Fan, and Hongyan Li. "Reduction of brittleness of fine sandy soil biocemented by microbial-induced calcite precipitation." *Geomicrobiology Journal* 39, no. 2 (2022): 135-147. https://doi.org/10.1080/01490451.2021.2019858
[41] Hu, Qizhi, Wensen Song, and Jianwen Hu. "Study of the Mechanical Properties and Water Stability of Microbially Cured, Coir-Fiber-Reinforced Clay Soil." *Sustainability* 15, no. 17 (2023): 13261. https://doi.org/10.3390/su151713261
[42] Liu, Peng, Yu Cheng, Long Chen, and Guang-hui Shao. "Application of microbial mineralization in the treatment of sintering red mud." *Journal of Central South University* 30, no. 9 (2023): 3057-3068. https://doi.org/10.1007/s11771-023-5381-x
[43] Hu, Qizhi, and Zekai Wang. "Experimental Study on Microbial Solidification of Gravel-Containing Silty Clay under Different Calcium Sources." *Geofluids* 2022, no. 1 (2022): 7321869. https://doi.org/10.1155/2022/7321869
[44] Zamani, Atefeh, Peng Xiao, Jason T. DeJong, Ross W. Boulanger, Daniel W. Wilson, and Trevor J. Carey. "MICP treatment to mitigate soil liquefaction-induced building settlements." In *IFCEE 2021*, p. 308-317. 2021. https://doi.org/10.1061/9780784483411.030
[45] Elam, Johanna, and Charlotte Björdal. "A review and case studies of factors affecting the stability of wooden foundation piles in urban environments exposed to construction work." *International Biodeterioration & Biodegradation* 148 (2020): 104913. https://doi.org/10.1016/j.ibiod.2020.104913
[46] Amjad, Usama Bin, Muhammad Shahid Siddique, Taha Shahid, Iftikhar Ahmed, Saleh M. Alogla, and Jawad Ahmad. "A study on microbial self-healing concrete using expanded perlite." *Bulletin of the Polish Academy of Sciences. Technical Sciences* 71, no. 5 (2023). https://doi.org/10.24425/bpasts.2023.146475
[47] Li, Yujie, Zhen Guo, Lizhong Wang, Hua Yang, Yilong Li, and Jianfeng Zhu. "An innovative eco-friendly method for scour protection around monopile foundation." *Applied Ocean Research* 123 (2022): 103177. https://doi.org/10.1016/j.apor.2022.103177
[48] Boob, Aashutosh Girish, Junyu Chen, and Huimin Zhao. "Enabling pathway design by multiplex experimentation and machine learning." *Metabolic Engineering* 81 (2024): 70-87. https://doi.org/10.1016/j.ymben.2023.11.006
[49] Hoffmann, Timothy D., Kevin Paine, and Susanne Gebhard. "Genetic optimisation of bacteria-induced calcite precipitation in Bacillus subtilis." *Microbial cell factories* 20 (2021): 1-19. https://doi.org/10.1186/s12934-021-01704-1
[50] Bandyopadhyay, Atrayee, Anwesha Saha, Diya Ghosh, Bomba Dam, Amiya K. Samanta, and Susmita Dutta. "Microbial repairing of concrete & its role in CO2 sequestration: a critical review." *Beni-Suef University Journal of Basic and Applied Sciences* 12, no. 1 (2023): 7. https://doi.org/10.1186/s43088-023-00344-1
[51] Tan, Linzhen, Xinyuan Ke, Qiu Li, Susanne Gebhard, Veronica Ferrandiz-Mas, Kevin Paine, and Wei Chen. "The effects of biomineralization on the localised phase and microstructure evolutions of bacteria-based self-healing cementitious composites." *Cement and Concrete Composites* 128 (2022): 104421. https://doi.org/10.1016/j.cemconcomp.2022.104421

[52] Jain, Surabhi, Chaolin Fang, and Varenyam Achal. "A critical review on microbial carbonate precipitation via denitrification process in building materials." *Bioengineered* 12, no. 1 (2021): 7529-7551. https://doi.org/10.1080/21655979.2021.1979862
[53] Li, Zhenfang, Aizhu Liu, Chunhui Sun, Haitao Li, Zheng Kong, and Haoran Zhai. "Biomineralization process of CaCO3 precipitation induced by Bacillus mucilaginous and its potential application in microbial self-healing concrete." *Applied Biochemistry and Biotechnology* 196, no. 4 (2024): 1896-1920. https://doi.org/10.1007/s12010-023-04634-3
[54] Song, He-Wei, Dong Li, Hao Qiu, Zhi-Guo Yu, Amit Kumar, Xiu-Xiu Yan, Fang-Yu Hu, Bao-Yu Wang, and Jing An. "Microbial-induced carbonate precipitation effectively prevents Pb2+ migration through the soil profile: Lab experiment and model simulation." *Science of The Total Environment* 927 (2024): 172268. https://doi.org/10.1016/j.scitotenv.2024.172268
[55] Xu, Fengli, and Dongxing Wang. "Review on soil solidification and heavy metal stabilization by microbial-induced carbonate precipitation (MICP) technology." *Geomicrobiology Journal* 40, no. 6 (2023): 503-518. https://doi.org/10.1080/01490451.2023.2208113
[56] Zhang, Y. S., Y. Liu, X. D. Sun, W. Zeng, H. P. Xing, J. Z. Lin, S. B. Kang, and L. Yu. "Application of microbially induced calcium carbonate precipitation (MICP) technique in concrete crack repair: A review." *Construction and Building Materials* 411 (2024): 134313. https://doi.org/10.1016/j.conbuildmat.2023.134313