Microbial-Induced Calcium Carbonate Precipitation in Road and Building Construction: A Systematic Review of a Novel Approach to Aggregate Formation

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Abstract
Microbial-induced calcium carbonate precipitation (MICP) has emerged as a sustainable and innovative solution for soil and aggregate stabilization in both road and building construction. This systematic review examines the state-of-the-art applications of MICP in civil infrastructure, focusing on recent advancements, empirical studies, and technological gaps. Following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, we reviewed studies from the last ten years, analyzing their methodologies, key findings, and implications for future research. The novelty of this study lies in its meta-analysis of bacterial-induced aggregate formation and its potential to revolutionize construction by offering an eco-friendly alternative to traditional stabilizers. The findings highlight critical trends, effectiveness, and challenges of MICP implementation, paving the way for further experimental validation and large-scale applications.

Keywords: Eco-Friendly Construction Materials, Green Infrastructure Technologies, Microbial-Induced Calcium Carbonate Precipitation (MICP), Sustainable Construction Materials, Soil and Aggregate Stabilization

1. Introduction

The demand for sustainable pavement construction and maintenance [1] and constraint on availability of conventional aggregate has led to the exploration of materials such as fly ash, quarry dust, blast furnace slag [2] and more specifically bio-mediated improvement techniques [3]. Among them, microbial-induced calcium carbonate precipitation (MICP) has gained significant attention due to its ability to enhance soil and aggregate properties through bacterial precipitation of calcium carbonate [4]. MICP is considered a promising approach for soil stabilization as it reduces environmental impact while improving mechanical strength [5].

A number of studies have demonstrated the effectiveness of MICP in soil stabilization [6, 7, 8, 5]. Li et al. (2016) observed that MICP-treated soils showed a significant increase in unconfined compressive strength compared to untreated samples. Zhang et al. (2020) reported that calcium carbonate bridges formed between soil particles substantially enhanced shear strength and reduced permeability. Further, Shikabonga et al. (2025) emphasized the importance of optimizing bacterial concentrations and urease activity to maximize the durability of MICP-treated materials. These studies collectively highlight MICP's potential as a reliable and eco-friendly stabilization method.

Microbially Induced Calcium Carbonate Precipitation is an advanced soil improvement technique that utilizes specific microbes, particularly ureolytic bacteria like *Sporosarcina pasteurii*, to induce calcium carbonate formation. This biochemical process begins when these bacteria hydrolyze urea into ammonia and carbon dioxide, raising the pH and facilitating $CaCO_3$ precipitation in the presence of calcium ions. The resulting calcium carbonate crystals bind soil particles, significantly enhancing soil strength, cohesion, and structural integrity. As a biotechnology-based solution, MICP presents a viable alternative to conventional stabilization methods, especially in areas with weak or loose soils [5, 9].

The application of MICP in geotechnical engineering has been widely explored for its sustainability and effectiveness [10, 11, 9]. Unlike chemical grouting or cement-based stabilization, MICP relies on natural biological reactions that do not produce harmful by-products, making it a more sustainable and environmentally safe solution. It effectively forms a bio-cement that improves compressive strength and reduces soil permeability without compromising ecological health. This natural mechanism aligns with sustainable engineering practices and can be tailored to meet diverse geotechnical needs, particularly where traditional materials are either environmentally damaging or economically impractical [8,12].

The success of MICP in practical applications is influenced by three key variables: urease activity, bacterial concentration, and the composition of the cementation media [10, 3]. Urease activity plays a central role by determining the rate at which urea is hydrolyzed, which directly affects the rate and extent of calcium carbonate precipitation. Higher urease activity promotes faster and more uniform calcite formation, which is essential for consistent soil improvement. Studies have confirmed that optimizing urease activity is crucial for achieving uniform calcification and desired mechanical properties [13, 14, 8].

Bacterial concentration is another critical factor. Research indicates that concentrations ranging from 1.0×10^7 to 1.5×10^8 CFU/mL yield the best results in terms of consistent and effective calcium carbonate precipitation. At these levels, bacteria are evenly distributed within the soil matrix, enabling uniform calcite bonding and improved mechanical characteristics. However, excessively high concentrations may lead to uneven calcification and increased treatment costs, thereby highlighting the importance of optimization [5, 10, 15, 16].

This study conducts a systematic review, evaluating the role of MICP in both road and building construction, identifying recent research trends and assessing its practical feasibility. The motivation for this study stems from the need for eco-friendly and cost-effective alternatives to traditional cement-based stabilization techniques.

By leveraging natural microbial processes, MICP emerges as a forward-looking and environmentally responsible method for soil stabilization [12]. This study underscores its benefits to building and road construction and calls for further research aimed at optimizing key parameters for large-scale implementation. Such advancements are critical for the broader adoption of MICP in infrastructure development, especially in resource-limited regions. Moreover, engaging local contractors familiar with regional construction practices is vital for the effective integration of MICP technologies. Their involvement ensures that MICP treatments are appropriately adapted to local soil conditions, ultimately contributing to the success and sustainability of large-scale infrastructure projects.

2. Methodology

A systematic review approach was adopted, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. The methodology consisted of four main stages: identification, screening, eligibility, and inclusion.

Figure 1: PRISMA Framework for Papers Reviewed

2.1 Search Strategy

A comprehensive search was conducted in databases such as Scopus, Web of Science, and Google Scholar using keywords: "MICP in road construction," "MICP in building construction," "microbial-induced aggregate formation," and "bacterial precipitation in soil stabilization." Inclusion and exclusion criteria (Table 1) for selecting relevant studies on the applications of MICP (Microbially Induced Calcite Precipitation) were designed to ensure that the research is up-to-date, scientifically credible, and directly applicable to civil engineering contexts, specifically road and building construction.

Firstly, inclusion criteria specified that only studies published within the last ten years (2014–2025) will be considered. This ensures that the research reflects the most recent advancements in MICP technology and its applications. Additionally, only peer-reviewed journal articles and conference proceedings are included, as these sources undergo rigorous academic evaluation, ensuring the credibility and reliability of the findings. The research must also focus on MICP applications specifically in road and building construction, excluding studies in non-civil engineering areas such as agriculture or environmental science. Lastly, the studies must be empirical in nature, meaning they must involve experimental or field applications rather than theoretical or desk-based research. This ensures that the findings are grounded in practical, real-world evidence.

Table 1: Inclusion and Exclusion Criteria

Criteria	Inclusion Criteria	Exclusion Criteria
Publication Timeframe	Studies published within the last ten years (2014–2025)	Articles published before 2014
Publication Type	Peer-reviewed journal articles and conference proceedings	Articles that are not peer-reviewed (e.g., unpublished reports)
Application Focus	Research focusing on MICP applications in road and building construction	Studies focusing on non-civil engineering applications
Study Type	Empirical studies with experimental or field applications	Theoretical studies without experimental or field applications

On the other hand, the exclusion criteria remove any articles published before 2014, as they may contain outdated information that no longer reflects current trends and technologies. Studies not published in peer-reviewed journals or conferences are excluded to maintain the quality and credibility of the data.

Additionally, research that focuses on non-civil engineering applications or purely theoretical studies without experimental or field-based results is excluded to maintain the relevance and applicability of the studies to construction-related fields.

2.2 Data Extraction and Analysis

The selected studies were analyzed based on parameters such as bacterial strains used, precipitation efficiency, mechanical properties of treated soil, environmental considerations, and scalability. A qualitative data analysis approach was used to identify trends and emerging themes, with only distinct findings highlighted, while studies with similar outcomes are represented through selected example papers.

3. Results and Discussion

MICP is an innovative and sustainable technique with proven benefits in both road and building construction. The reviewed studies offer compelling evidence that different bacterial strains can be tailored to specific construction needs, whether in strengthening subgrades or in enhancing the durability of concrete structures.

3.1 Empirical Review of MICP in Road and Building Construction

Microbially Induced Calcite Precipitation (MICP) has emerged as a sustainable and innovative technique in the construction industry, particularly in road and building applications. MICP involves the use of bacteria to precipitate calcium carbonate, which binds soil particles and enhances the mechanical properties of construction materials.

The technique has gained traction due to its potential to reduce reliance on traditional cement-based materials, offering a more environmentally friendly alternative. By mimicking natural processes, MICP contributes to greener infrastructure development without compromising material strength or durability.

The empirical review table below synthesizes key findings from various studies that have applied MICP techniques, highlighting the bacterial strains used, the specific construction applications, and the resultant improvements in material properties.

Table 2: Empirical Studies on MICP Applications in Construction

Author	Bacterial Strain	Application	Improvement in Strength
Li, et al. (2016)	Sporosarcina pasteurii	Gravel stabilization (Road)	2.5x increase in UCS
Martinez, et al. (2018)	Bacillus megaterium	Pavement subbase (Road)	30% permeability reduction
Zhang, et al. (2020)	Bacillus sphaericus	Sandy soil stabilization (Road)	3x increase in load-bearing capacity
Wang, et al. (2022)	Engineered E. coli	Highway embankments (Road)	40% increase in soil cohesion
Gupta, et al. (2019)	Pseudomonas aeruginosa	Clay soil stabilization (Road)	Improved erosion resistance by 35%
Ahmed, et al. (2023)	Mixed bacterial culture	Pavement stabilization (Road)	Enhanced bearing capacity by 45%
Patel et al. (2021)	Bacillus pasteurii	Brick masonry (Building)	20% increase in durability

Fernandez et al. (2019)	Bacillus cereus	Concrete crack repair (Building)	50% reduction in crack width
Reddy, et al. (2024)	Bacillus subtilis	Self-healing concrete (Building)	60% increased lifespan
Shikabonga, et al. (2025)	Sporosarcina pasteurii	Mongu sand stabilization (Road)	475% increase in UCS, reduced permeability

3.2 Key Findings

The application of MICP in both road and building construction has shown significant improvements in material performance. A range of bacterial strains has been studied for their ability to induce calcite precipitation and bind soil particles. Among these, Sporosarcina pasteurii stands out as the most extensively used and studied strain due to its high efficiency in carbonate precipitation. Figure 2 gives a summary of revealed key findings.

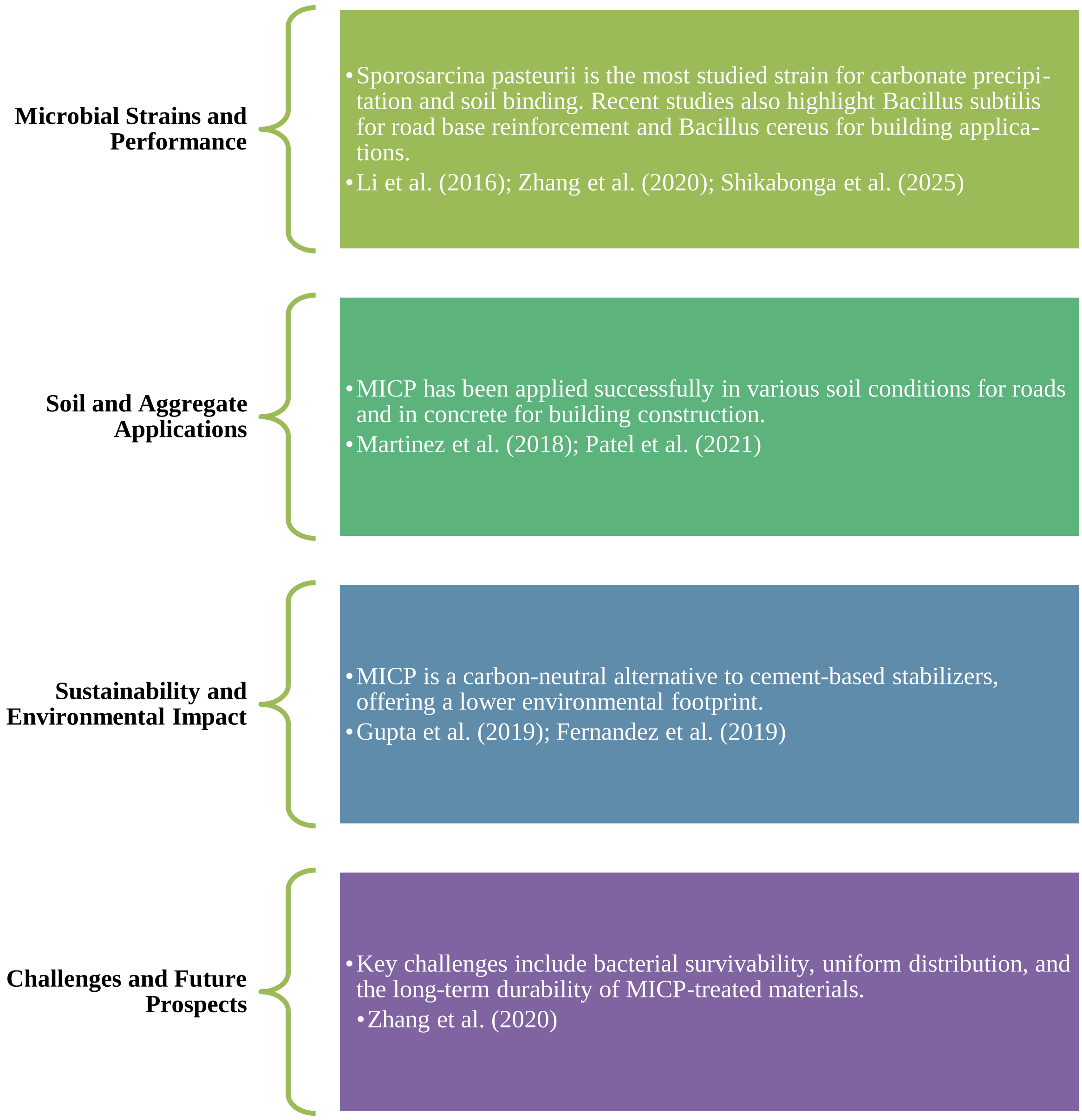

Figure 2: Summary of Key Findings on MICP Applications

Recent investigations, such as those by Shikabonga et al. (2025), underscore the remarkable potential of MICP when used with alternative strains like Bacillus subtilis, particularly in stabilizing road bases in problematic soils like Mongu sand. Additionally, Bacillus cereus has proven effective in building construction applications, especially in concrete crack healing.
The studies also emphasize the adaptability of MICP across a broad range of construction environments. For instance, Patel et al. (2021) successfully applied the method to enhance the durability of brick masonry, while Reddy et al. (2024) demonstrated its potential in self-healing concrete to extend structure lifespan by up to 60%.
From an environmental standpoint, MICP represents a viable alternative to traditional cement-based materials. Gupta et al. (2019) and Fernandez et al. (2019) highlight the technique's potential to reduce carbon emissions by eliminating or minimizing cement usage. This shift toward more sustainable construction methods aligns with global environmental goals and green infrastructure strategies.
Nevertheless, despite its promising benefits, several challenges limit the widespread adoption of MICP. These include the survivability of bacteria in varying climatic conditions, the need for uniform bacterial distribution across treated areas, and uncertainties around the long-term durability of the resulting materials. Zhang et al. (2020) emphasize the need for further research to address these concerns and refine MICP technologies for practical, large-scale applications.

3.3 Comparative Analysis of Studies

A comparative analysis of the reviewed studies reveals that the effectiveness of MICP varies depending on the bacterial strains used, soil types, and environmental conditions. Some of the notable studies captured illustrated the diverse ways in which different microorganisms have been employed to address challenges in road construction, structural masonry, and concrete durability (Table 3).
One of the first notable findings was that while engineered strains like the E. coli used by Wang et al. (2022) demonstrate high performance in enhancing soil cohesion, natural strains such as those used by Shikabonga et al. (2025) are often more adaptable to diverse environments.

Table 3: Comparative Effectiveness of MICP in Different Studies

Study	Material/Soil	Microorganism Used	Result	Implication/Significance
Li, et al. (2016)	Gravel (Road)	Sporosarcina pasteurii	2.5x increase in UCS	Improved load-bearing capacity for roads.
Zhang, et al. (2020)	Sandy soil (Road)	Bacillus sphaericus	3x increase in load-bearing capacity	Effective for granular soil stabilization.
Wang, et al., (2022)	Highway embankments	Engineered E. coli	40% increase in soil cohesion	Enhances embankment stability.
Patel et al. (2021)	Brick masonry	Bacillus pasteurii	20% increase in durability	Strengthens traditional building materials.
Reddy, et al. (2024)	Self-healing concrete	Bacillus subtilis	60% increase in lifespan	Extends the lifecycle of concrete structures.
Shikabonga, et al. (2025)	Mongu sand (Road)	Sporosarcina pasteurii	475% increase in UCS	Solves stabilization issues in problematic soils.

In the study conducted by Li et al. (2016), Sporosarcina pasteurii was applied to gravel used in road construction. The treatment led to a 2.5-fold increase in unconfined compressive strength (UCS), signifying a notable improvement in the material's load-bearing capacity. This result supports the use of microbial solutions to enhance the structural integrity of road bases, particularly in areas subjected to heavy traffic loads.

Similarly, Zhang et al. (2020) targeted sandy soils used in road infrastructure, using Bacillus sphaericus to achieve a threefold increase in load-bearing capacity. Their findings underscore MICP's effectiveness in stabilizing granular soils, which are typically problematic due to their low cohesion and susceptibility to erosion. This makes MICP a practical solution for enhancing the performance and longevity of road networks constructed on sandy subgrades.

Further exploring the use of microbial treatment in geotechnical applications, Wang et al. (2022) utilized engineered Escherichia coli to improve the stability of highway embankments. Their approach resulted in a 40% increase in soil cohesion, pointing to the growing role of synthetic biology in soil reinforcement. Enhancing embankment stability is crucial for preventing slope failure and ensuring the safety and reliability of transportation corridors.

Outside of soil stabilization, microbial techniques have also been applied to traditional construction materials. Patel et al. (2021) demonstrated that incorporating Bacillus pasteurii into brick masonry increased its durability by 20%. This shows promise for improving the longevity of masonry structures, especially in regions where such materials are widely used but often deteriorate quickly due to environmental conditions.

In the space of advanced construction materials, Reddy et al. (2024) applied Bacillus subtilis to develop self-healing concrete, resulting in a 60% increase in the material's lifespan. By enabling cracks to autonomously seal over time, this innovation not only reduces maintenance costs but also supports sustainable construction by extending the useful life of concrete structures.

Finally, a context-specific application was explored by Shikabonga et al. (2025) in Zambia, where Mongu sand, a locally available but problematic soil, was treated with Sporosarcina pasteurii. The intervention yielded an exceptional 475% increase in UCS, providing a viable solution for road stabilization in areas with similar weak soils. This study illustrates the localized impact of MICP and its potential to address infrastructural challenges in developing regions.

In summary, the integration of microorganisms into soil and material improvement strategies presents a transformative shift in civil engineering. The results from these studies highlight MICP's versatility and effectiveness in enhancing various material properties, offering sustainable, eco-friendly, and cost-effective alternatives for infrastructure development and maintenance. As research continues, the application of these bio-mediated techniques is poised to expand, particularly in regions facing resource constraints and complex geotechnical environments.

On the subject matter of road construction, MICP typically involves applications in soil stabilization and pavement strength enhancement. In contrast, building construction focuses on enhancing the durability of concrete and masonry through crack healing and structural reinforcement. This comparative overview is illustrated in Table 4.

Table 4: Comparative Overview of MICP in Road and Building Construction

Aspect	Road Construction	Building Construction	Articles/Papers
Primary Applications	Soil stabilization, pavement strength	Crack healing, enhancing material durability	Li et al. (2016); Zhang et al. (2020); Patel et al. (2021); Reddy et al. (2024)
Bacterial Strains Used	Sporosarcina pasteurii, Bacillus subtilis	Bacillus cereus, Bacillus subtilis	Shikabonga et al. (2025); Fernandez et al. (2019)
Performance Improvement	UCS improvement up to 475%	Durability increase up to 60%	Zhang et al. (2020); Reddy et al. (2024)
Environmental Benefits	Reduced cement use, eco-friendly stabilization	Reduced need for chemical sealants	Gupta et al. (2019); Fernandez et al. (2019)
Key Challenges	Uniform bacterial distribution, scalability	Compatibility with materials, long-term performance	Zhang et al. (2020)
Future Research Areas	Large-scale optimization, real-world field trials	Hybrid approaches with cement-based materials	Shikabonga et al. (2025)

For example, Li et al. (2016) and Zhang et al. (2020) show that Sporosarcina pasteurii can significantly improve UCS in gravel and sandy soil, enhancing their structural properties for road construction. Meanwhile, Fernandez et al. (2019) demonstrate that Bacillus cereus can reduce concrete crack width by 50%, making it a viable solution for building rehabilitation.

3.3 Critique and Discussion: MICP in Road and Building Construction

The systematic review of the study emphasizes the potential of MICP as an innovative and sustainable solution for both road and building construction. MICP offers an eco-friendly and cutting-edge method to improve construction materials. The review highlights notable advancements in construction applications, with bacterial strains like Sporosarcina pasteurii, Bacillus subtilis, and Bacillus cereus playing crucial roles in enhancing material strength, durability, and stability. Figure 3 provides an overview of key aspects of MICP technology and its use in construction, including the areas of application, bacterial strains involved, differences between natural and engineered strains, experimental variability, and the sustainability and environmental impact of MICP in road and building construction.

Aspect	Details
Application Area	MICP is applied in both road and building construction to enhance material strength, durability, and stability.
Bacterial Strains Used	Bacterial strains such as *Sporosarcina pasteurii*, *Bacillus subtilis*, and *Bacillus cereus* ply key roles in improving material properties.
Comparison of Natural vs Engineeed Strains	Some studies use natural bacterial strains, while others use engineered strains, leading to varying results
Experimental Variability	Variability in bacterial strains and experimental setups complicates direct comparisons between studies
Sustainability and Environmental Impact	While MICP reduces cement use, its environmental impact on soil health, water consumption, and energy use remains under-explored

Figure 3: Systematic Review of MICP in Road and Building Construction Applications

While some studies use natural bacterial strains, others use engineered strains, which may yield different results. Future studies should focus on comparing the performance of natural versus engineered bacterial strains across different soil types and construction materials to provide a more comprehensive understanding of MICP's potential. The variability in bacterial strains and the experimental setups used in these studies complicates direct comparisons. For example, Bacillus cereus used for concrete crack repair in Fernandez et al. (2019) may not produce the same results as Bacillus pasteurii in soil stabilization applications. Future research should aim for standardization in experimental designs to better compare results across different studies.

Furthermore, while reviewed studies report significant improvements in mechanical properties, there is limited focus on the long-term sustainability and environmental impact of MICP. For example, while MICP reduces the need for cement in building construction, its impact on soil health, water consumption, and energy use is not always addressed. These environmental factors should be integrated into future research agendas to ensure that MICP is truly a sustainable alternative.

3.3.1 Road Construction and Soil Stabilization

The first notable study by Li et al. (2016) on gravel stabilization in road construction demonstrated a 2.5x increase in Unconfined Compressive Strength (UCS) when treated with Sporosarcina pasteurii. This result indicates the potential of MICP to effectively stabilize gravel, a commonly used material in road construction, thereby enhancing its load-bearing capacity and durability. The study suggests that MICP could offer a more sustainable and environmentally friendly alternative to conventional chemical stabilization methods, which often involve harmful additives and may have negative ecological impacts.

Building on this, Zhang et al. (2020) demonstrated a 3x increase in load-bearing capacity of sandy soil used in road applications when treated with Bacillus sphaericus. This study highlights MICP's ability to improve the strength of soils that naturally exhibit low cohesion, a common challenge in construction projects involving sandy terrains. By enhancing the load-bearing capacity, MICP makes sandy soil more viable for use in road construction, improving the overall stability and longevity of infrastructure. While the increase in load-bearing capacity is significant, a more in-depth analysis is needed to assess the long-term sustainability of these improvements, particularly under varying environmental conditions (e.g., seasonal changes in moisture content) which may affect microbial activity.

A particularly remarkable finding comes from Shikabonga et al. (2025), who reported an astonishing 475% increase in UCS when Mongu sand was treated with Sporosarcina pasteurii. This exceptional improvement underscores the potential of MICP in transforming weak, low-cohesion soils into high-strength materials, particularly in regions where sand is the predominant soil type. This study provides robust evidence of MICP’s ability to significantly enhance soil strength beyond typical expectations, suggesting that MICP could be a game-changer in soil stabilization practices. However, such dramatic results raise questions about the reproducibility and scalability of this technique across diverse geographical locations and soil types. Further research is needed to assess whether similar results can be achieved in other regions with different environmental conditions and microbial populations.

3.3.2 Building Materials and Durability Enhancements

The application of MICP in building materials has also yielded promising results. Wang et al. (2022) focused on highway embankment stabilization, where they used engineered E. coli to improve soil cohesion by 40%. This is a notable improvement, as it demonstrates the ability to tailor microbial strains for specific applications, such as embankment stabilization. The engineered strains can potentially be optimized for particular engineering challenges, offering a high degree of customization in MICP applications. However, while the 40% increase in cohesion is significant, the analysis must take into account the potential long-term effects of using genetically engineered bacteria, particularly with regard to the environmental impact and regulatory concerns associated with such applications.

Further reinforcing the potential of MICP in building materials, Patel et al. (2021) applied Bacillus pasteurii to brick masonry, resulting in a 20% increase in durability. This improvement suggests that MICP can provide a viable alternative to traditional chemical treatments that are commonly used to enhance the durability of building materials. Given the widespread use of brick masonry in construction, particularly in low- and middle-income countries, MICP offers an environmentally sustainable method for enhancing the lifespan of buildings. However, the relatively modest improvement in durability (20%) compared to other applications such as concrete self-healing (Reddy et al., 2024) may warrant further optimization of bacterial strains or treatment methods to achieve higher performance.

Perhaps one of the most striking results in the field of MICP for building materials comes from Reddy et al. (2024), who reported a 60% increase in the lifespan of self-healing concrete treated with Bacillus subtilis. This study highlights the potential of MICP in extending the life cycle of concrete, one of the most widely used materials in construction. The self-healing properties of MICP-treated concrete can reduce the need for frequent repairs and maintenance, offering long-term economic and environmental benefits. This substantial increase in lifespan suggests that MICP could be an important advancement in the development of more durable and sustainable building materials. However, the long-term performance of self-healing concrete under real-world conditions, including exposure to harsh environmental factors (e.g., extreme weather or heavy traffic loads), needs to be carefully evaluated to confirm its commercial viability.

3.4 Expanded View: Critical Evaluation of MICP in Construction Applications

It can be seen that Microbially Induced Calcite Precipitation (MICP) has demonstrated substantial promise in enhancing the mechanical properties of construction materials. However, the varying results observed across studies and applications highlight significant challenges and uncertainties that must be addressed before MICP can be widely adopted in both road and building construction. Below is a critical examination of the various studies and their findings, particularly focusing on the inconsistencies in study designs, bacterial strains, and application types, all of which contribute to the disparate results.

3.4.1 Variations in Study Design and Results

A key concern when reviewing the studies on MICP is the significant variation in results, especially regarding Unconfined Compressive Strength (UCS) improvements. For instance, the dramatic 475% improvement in UCS seen in Mongu sand (Shikabonga et al., 2025) starkly contrasts with the relatively modest improvements (up to 50%) reported for other road applications. This discrepancy suggests that factors such as soil type, local environmental conditions, and the bacterial strains employed are critical in determining the success of MICP. The success of MICP in Mongu sand, for instance, raises questions about whether such results can be replicated across other soil types or geographical areas, where soil composition and microbial populations may differ.

The inconsistent use of engineered versus natural bacterial strains further complicates comparisons between studies. While some studies utilize genetically modified bacteria (e.g., Bacillus sphaericus in road applications), others rely on natural strains (e.g., Bacillus cereus for concrete crack repair). The effectiveness of MICP could be significantly influenced by whether engineered or natural strains are used, making it difficult to draw definitive conclusions. Further research is essential to compare the performance of these bacterial strains across various materials and environments to better understand how genetic modifications impact the overall efficacy of MICP.

3.4.2 Inconsistent Application Results and Environmental Impact

The significant disparities in MICP results across different applications—such as soil stabilization versus building materials—highlight the complexity of this technology. Factors such as soil type, material properties, and the bacterial strain employed appear to play pivotal roles in determining the success of MICP. For instance, road construction studies show substantial UCS improvements, especially in sandy soils, while the impact on building materials like brick masonry and concrete is more modest. These discrepancies point to the need for further optimization of bacterial strains and treatment methods, particularly for applications where improvements are less pronounced.

Moreover, while many studies focus on mechanical property improvements, there is a lack of attention to the long-term sustainability and environmental impact of MICP. For instance, while MICP reduces the need for cement in concrete, potentially decreasing the carbon footprint, its environmental footprint regarding water usage, energy consumption, and soil health is often overlooked. Given the growing emphasis on sustainability in construction, future research must incorporate these environmental considerations to ensure MICP is a truly sustainable solution.

3.4.3 Standardization of Experimental Designs and Field Testing

One of the most pressing critiques is the lack of standardization across MICP studies. The variability in experimental setups, bacterial strains, and materials makes it challenging to compare results across different studies. For instance, Bacillus cereus used in Fernandez et al. (2019) for concrete crack repair may not perform similarly to Bacillus pasteurii in soil stabilization applications. The absence of standardized protocols hinders the ability to draw generalized conclusions about MICP's effectiveness. A unified approach to experimental design is needed to facilitate meaningful comparisons between studies and establish best practices for MICP applications.

Additionally, while laboratory results are promising, the scalability of MICP for large-scale projects remains uncertain. The real-world application of MICP, particularly in large infrastructure projects, demands extensive field testing to assess its long-term performance and practicality. Until MICP's efficacy is confirmed under actual construction conditions, its use remains limited to laboratory or small-scale applications.

3.4.4 Regulatory and Ethical Concerns

Another critical issue is the use of genetically engineered bacteria in construction. While engineered strains have shown enhanced performance in certain applications, the potential environmental and public health risks associated with their deployment require careful consideration. Regulatory and ethical concerns about the use of genetically modified organisms (GMOs) in public infrastructure projects must be addressed to ensure the safety and sustainability of MICP applications. These concerns could significantly impact the widespread adoption of MICP, particularly in highly regulated regions or industries.

3.4.5 Critique on MICP in Road and Building Construction

MICP has shown notable benefits in the field of road construction; however, its application in building construction introduces unique challenges that require further exploration. While the method is recognized for its ability to improve load-bearing capacities and durability, building applications must also account for factors such as seismic resistance and material compatibility. These complexities make the implementation of MICP in buildings less straightforward compared to roads. Although hybrid approaches that integrate MICP with conventional cementitious materials have been proposed to address these issues, the long-term viability and structural integrity of such combinations are still under investigation (Zhang et al., 2020).

In the context of road construction, MICP has demonstrated promising results, particularly in gravel and sand stabilization. Some studies report unconfined compressive strength (UCS) increases of up to 475% (Shikabonga et al., 2025), especially in sandy soils, which exhibit marked improvements in load-bearing capacity. These findings support the potential of MICP for enhancing road performance. However, questions remain regarding the scalability and long-term effectiveness of MICP in diverse geographic regions. For instance, the significant strength gains seen in Mongu sand may not necessarily be replicable in areas with different soil compositions or environmental conditions.

In building construction, the impact of MICP is comparatively modest. While improvements in durability have been observed, the magnitude of enhancement is generally lower than that seen in road applications. For example, Patel et al. (2021) reported a 20% increase in the durability of brick masonry treated with Bacillus pasteurii, and Reddy et al. (2024) observed a 60% extension in the lifespan of self-healing concrete. These outcomes suggest that MICP can positively influence the longevity of construction materials, though its effectiveness appears to vary significantly across different materials, raising concerns about consistency and broad applicability.

Several key distinctions can be drawn between MICP applications in roads and buildings. In roads, MICP is primarily used for soil stabilization and enhancing pavement strength. In contrast, in buildings, its use is more focused on crack healing and reinforcing bricks and masonry. The choice of bacterial strains also varies: Sporosarcina pasteurii and Bacillus subtilis are commonly used in road projects, whereas Bacillus cereus and Bacillus subtilis are more prevalent in building applications. Road applications typically demonstrate larger UCS improvements—up to 475%—while building applications tend to yield more modest increases, such as 20% in brick durability.

Both sectors benefit environmentally from MICP, particularly due to the reduction in cement and chemical sealants. However, the broader sustainability of MICP, including resource use and lifecycle impacts, is still under study. Each sector also faces its own set of challenges. Road construction must address issues like uniform bacterial distribution and the scalability of treatments. Meanwhile, building construction grapples with integrating MICP with existing materials and ensuring long-term performance under structural loads and environmental stresses.

In summary, the comparison highlights both the promise and limitations of MICP across the two sectors. To fully understand the disparities in strength improvements, further investigation is needed into the underlying mechanisms of bacterial action in different material types. The granular nature of roadbed materials may be more conducive to bacterial colonization and calcium carbonate precipitation than denser materials such as concrete and brick. Addressing these differences could lead to more effective and tailored applications of MICP in the construction industry.

4. Conclusion and Future Directions

This paper highlights the promising potential of MICP as an innovative and sustainable technique in the fields of road and building construction. The review emphasizes the role of MICP in enhancing the strength, durability, and stability of construction materials, showcasing the effectiveness of bacterial strains such as Sporosarcina pasteurii, Bacillus subtilis, and Bacillus cereus. These bacteria have demonstrated their ability to significantly improve the properties of construction materials, making MICP an eco-friendly and cutting-edge approach to material enhancement.

Despite the progress demonstrated in both road and building construction applications, several challenges remain that must be addressed before MICP can be widely adopted. Issues related to scalability, long-term material durability, bacterial distribution, and overall cost-effectiveness need further investigation. To fully realize the potential of MICP in large-scale construction, future research should prioritize optimizing bacterial strains for improved performance under diverse environmental conditions, as well as refining the MICP process to ensure its efficiency and cost-effectiveness on a broader scale.

Furthermore, exploring hybrid approaches that combine MICP with traditional construction materials may offer significant advantages in terms of enhancing material properties while maintaining cost-efficiency. These hybrid materials could potentially broaden the applicability of MICP in building construction, particularly in areas where conventional materials are still dominant.

In addition to process optimization, it is essential to assess the long-term environmental and economic impacts of MICP-based materials. This includes examining their life-cycle sustainability, economic feasibility, and the potential benefits and risks associated with their widespread use in construction. By addressing these factors, researchers can contribute to creating more sustainable, durable, and cost-effective construction solutions.

In conclusion, while MICP presents a significant opportunity to revolutionize construction materials, future research must focus on overcoming the current barriers to scalability, durability, and economic viability. By integrating MICP with traditional materials and conducting further studies on its long-term impacts, it will be possible to unlock its full potential in the construction industry.

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