

# Microbial-induced hydrated magnesium carbonate for stabilisation of crushed rock base in road pavement

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**ABSTRACT:** Microbial-Induced Hydrated Magnesium Carbonation (MIHMC) is an emerging technique that leverages ureolytic bacteria metabolism to carbonate Reactive Magnesium Oxide (RMO), thereby producing Hydrated Magnesium Carbonate (HMC), simultaneously strengthening soils and sequestering CO<sub>2</sub>. This study assesses the feasibility of using MIHMC to stabilise crushed rock base (CRB) as a base material for road pavement construction. In this work, an experimental programme was conducted to examine the influence of various factors on the mechanical properties of MIHMC-treated CRB road base material, as measured by the unconfined compressive strength (UCS) test after 7 and 28 days of curing. These factors included RMO content, urea concentration, urease activity, and gradation dust ratio. The results indicate that the UCS values increased consistently with higher urea concentrations, greater RMO dosages, and longer curing durations. Higher urease activity significantly enhanced strength development, highlighting the importance of the early-stage carbonate formation. In addition, modifying the CRB gradation to increase the proportion of 75- $\mu$ m fines further improved the strength due to enhanced particle packing. Overall, the findings demonstrate the potential of MIHMC to improve the strength characteristics of CRB, thereby supporting its use as a sustainable and innovative stabilisation technique in road construction.

**KEYWORDS:** Microbial-Induced Hydrated Magnesium Carbonate (MIHMC), bio-cementation, crushed rock base, ground improvement, road pavement.

## 1 INTRODUCTION

Soil stabilisation is a critical step in road construction, aimed at enhancing the mechanical and geotechnical properties of the ground to ensure pavement integrity and extend its service life. Usually, roads are more prone to settlement, cracking, and long-term deterioration without effective soil stabilisation. Traditional soil stabilisation methods often rely on Portland cement and lime (Barbero-Barrera et al., 2020); however, such chemical binders are associated with environmental concerns, including high carbon emissions and energy consumption (Obuzor et al., 2012). For instance, the manufacturing process of Portland cement is responsible for approximately 5% to 8% of global anthropogenic CO<sub>2</sub> emissions annually, accounting for nearly 12% to 15% of total industrial energy consumption due to the high thermal demands of kiln operations (Fadayini et al., 2021; Cheng et al., 2023). Consequently, there is a pressing need for environmentally friendly alternatives that provide comparable or superior soil stabilisation performance.

Microbial-Induced Carbonate Precipitation (MICP) has recently gained attention as a sustainable and innovative method for soil stabilisation (Wang et al., 2023). The process of this technique employs ureolytic bacteria to hydrolyse urea, resulting in the formation of calcium carbonate (CaCO<sub>3</sub>) or calcite crystals that precipitate within the soil pores (Cheng et al., 2017; Liu et al., 2023). Such precipitates link the soil particles together, thereby improving soil strength and stability (DeJong et al., 2010). Despite its proven effectiveness, MICP encounters practical challenges that limit its widespread application on a large scale. One of the main challenges is that attaining the desired level of cementation usually requires multiple treatment cycles, during which CaCO<sub>3</sub> precipitates gradually accumulate within the soil pores. The repeated treatment cycle increases operational complexity, cost and duration of the treatment process, making it less feasible for field implementation. Moreover, the continued introduction of

bacterial and cementation solutions can cause pore clogging near the injection zones, which impedes further reactant transport and limits uniform CaCO<sub>3</sub> distribution, thereby restricting soil strength development if higher levels of cementation are needed. To address such limitations, microbial-induced hydrated magnesium carbonate (MIHMC) has been recently introduced as an effective alternative cementation technique, recognised for its lower energy demand, reduced greenhouse gas emissions, and minimal environmental impact (Wang et al., 2025). This soil stabilisation technique involves creating hydrated magnesium carbonate (HMC) using ureolytic bacteria. In this process, Reactive Magnesium Oxide (RMO) reacts with water to form brucite, which, in the presence of a carbonate source produced from urea hydrolysis, subsequently transforms into HMC. The produced HMC fills the voids between soil particles and binds them together, forming a solid matrix that can withstand external forces. This innovative approach enhances the strength of the stabilised materials and contributes to the carbon capture process (Gardeh et al., 2022; Zhang et al., 2024); hence, aligning with broader sustainability objectives. However, the literature on the use of the MIHMC technique for soil stabilisation remains limited, particularly with the performance of crushed rock base (CRB) in road construction. The work presented in this study thus aims to address this knowledge gap.

This paper explores the feasibility of stabilising CRB using MIHMC for road construction. The effects of varying RMO content, urea concentration, bacterial cell density and dust ratio were investigated to evaluate their influence on the efficiency and performance of the MIHMC process. Unconfined Compressive Strength (UCS) tests were conducted to assess the geomechanical properties of the MIHMC-stabilised CRB under varying treatment conditions.

## 2 MATERIALS AND METHODS

### 2.1 Crushed Rock Base (CRB)

The Crushed Rock Base (CRB) used in this study was obtained from a local quarry. The CRB gradation was evaluated according to the specifications of the Main Roads of Western Australia (MRWA) (2023) to ensure compliance with the requirement for use as a base layer material. The CRB was modified to include two values of dust ratio (DR), defined as the ratio of the percentage passing by mass through the 0.075 mm sieve to that passing through the 0.425 mm sieve. Two DR values were selected to be 0.38 and 0.53, which fall within the acceptable range of 0.35 to 0.60 specified by the MRWA. The particle size distribution of the CRB material with the two DR values is presented in Figure 1, demonstrating a well-graded material spanning the full range of particle sizes.

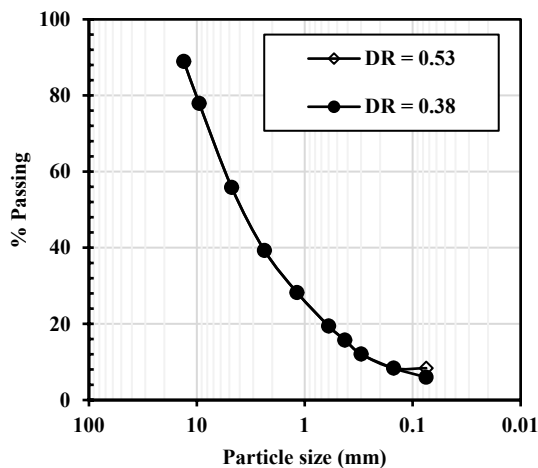


Figure 1. Particle size distribution of Crushed Rock Base (CRB) with varying Dust Ratio (DR).

### 2.2 Reactive Magnesium Oxide (RMO)

The Reactive Magnesium Oxide (RMO) used in this study was a laboratory-grade, light, white, fluffy powder with a purity of 95%, supplied by Chem-Supply. Varying concentrations of 2, 4, 6 and 8% by dry weight of CRB were used to stabilise the CRB material.

### 2.3 Ureolytic Bacterial Suspension and Carbonation Reagent

The ureolytic bacteria used in this study were a *Bacillus pasteurii* strain isolated in a previous study conducted by Al-Thawadi and Cord-Ruwisch (2012). The bacterial culture was grown in a nutrient-rich medium composed of 20 g/L yeast extract, 18 g/L ammonium sulfate and 0.02 mM nickel chloride, with the pH of the solution adjusted to 9.25 to enhance urease activity. The medium was sterilised by autoclaving at 121°C for 15 minutes. Following sterilisation, the isolated *Bacillus* strain was inoculated into the growth medium and incubated in a rotary shaker at 37°C for 24 hours to allow for active cell growth. Upon completion of the incubation period, the bacterial suspension was harvested and stored at 4°C until use. The culture was subsequently concentrated or diluted to achieve specific urease activity levels required for the experiments. The urease activity of the bacterial suspensions used in this study was measured at 8.67 U/mL and 16.45 U/mL, corresponding to optical density (OD<sub>600</sub>) values of 1.36 and 2.42, respectively.

The carbonation reagent used in this study is urea (purity > 95%), which was obtained from Chem Supply. The urea was

dissolved directly in the bacterial culture at varying concentrations of 0.5, 1.0 and 1.5 M before being mixed with the CRB and RMO blends.

### 2.4 Sample Preparation and Testing

Before sample preparation, the compaction characteristics of the Crushed Rock Base (CRB) treated with different contents of Reactive Magnesium Oxide (RMO) were evaluated using a modified compaction method, following the procedure outlined in WA 133.1 (2022). The results are presented in Table 1, which shows that the Optimum Moisture Content (OMC) increases with higher RMO contents, reflecting a greater water demand due to the high specific surface area of the RMO, which promotes water absorption within the treated CRB. On the other hand, the Maximum Dry Density (MDD) increased slightly with increasing RMO content up to 6%, after which it remained relatively constant. This plateau in the MDD at higher RMO content (above 6%) may be attributed to particle interference and reduced packing efficiency, where excess fine RMO particles begin to disrupt the dense arrangement of the coarser crushed rock particles, thereby limiting further improvement in the MDD.

Table 1. Compaction characteristics of CRB modified with varying RMO content.

RMO content (%)	OMC (%)	MDD (KN/m <sup>3</sup> )
2	4.27	21.22
4	4.56	21.47
6	5.50	22.08
8	6.20	22.06

The samples were prepared by mixing a predetermined weight of CRB, having a DR of 0.53, with the designated amounts of RMO based on the specified concentrations (i.e., 2, 4, 6, and 8%). Thereafter, the urea was mixed with the bacterial culture at the OMC, according to the specified molar concentrations of 0.5, 1.0, and 1.5 M, and stirred for 1 minute to ensure complete dissolution. The resulting solution was then thoroughly mixed with the CRB–RMO blend to ensure uniform distribution. Following mixing, Unconfined Compressive Strength (UCS) test samples with a diameter of 105 mm and a height of 115 mm were prepared by compacting the admixture into PVC moulds in five layers using the modified Proctor compaction hammer. After compaction, the samples were demoulded, wrapped in plastic film and allowed to cure before testing. The UCS test was conducted in accordance with the guidance outlined in WA 143.1 (2023), using a strain rate of 1% per minute on samples cured for 7 and 28 days to assess the impact of RMO carbonation.

## 3 RESULTS AND DISCUSSION

### 3.1 Impact of Urea Concentration, RMO Content and Curing Time on UCS

Figure 2 presents the UCS results of the CRB-treated samples with varying RMO contents at different urea concentrations, cured for 7 and 28 days. Irrespective of the curing time, the results indicate a progressive increase in the UCS with increasing urea concentration across all RMO contents. For instance, at an RMO content of 2%, the UCS values at 7 days of curing were approximately 1.8, 2.1 and 2.3 MPa at urea concentrations of 0.5, 1.0 and 1.5 M, respectively (Figure 2a). Similarly, at a higher RMO content of 8%, the corresponding UCS increased to approximately 6.0, 6.8 and 8.8 MPa, respectively. A similar trend is also observed for specimens cured for 28 days (Figure 2b). Such a quantitative improvement in the UCS values of treated CRB mixed with a specific RMO content, as the urea concentration increases, can be attributed to

the greater availability of carbonate ions generated from urea hydrolysis, which promotes more extensive carbonation of the hydrated RMO and contributes to CRB matrix bonding and strength gain. In addition to this strength dependence on the urea concentration, the overall influence of the RMO content on the UCS values of treated CRB was more pronounced. For instance, increasing the RMO content from 2 to 4% at a typical urea concentration of 1.5 M resulted in a UCS increase of 116% and 58% at 7 and 28 days, respectively. A further increase in the RMO content to 6% resulted in additional strength gains of 49% and 29% at 7 and 28 days, respectively. The peak UCS performance was observed at an 8% RMO, which can be attributed to the higher availability of RMO for carbonation, leading to an increased formation of HMC that enhances particle bonding and matrix densification.

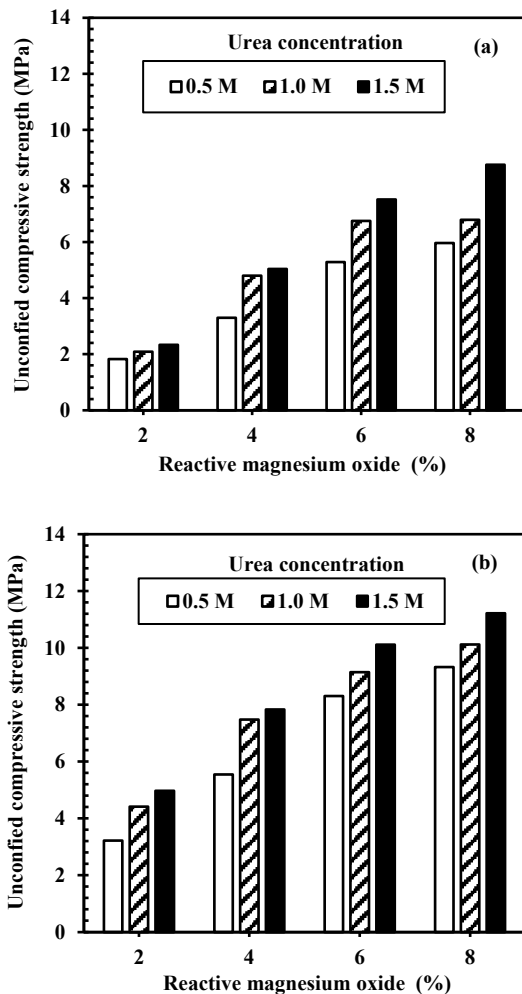


Figure 2. Unconfined Compressive Strength (UCS) of Crushed Rock Base (CRB) material treated with varying reactive Magnesium Oxide (RMO) and urea concentrations after: (a) 7 days; and (b) 28 days of curing.

The curing time also played a significant role in enhancing CRB strength, with all mixtures showing increased UCS values from 7 to 28 days. For instance, at an RMO content of 2% and a urea concentration of 1.0 M, the UCS increased from 2.09 MPa to 4.42 MPa, indicating an approximately 111% increase in the UCS. Additionally, at an RMO content of 8% and a urea concentration of 1.0 M, the UCS increased from 6.79 MPa to 9.84 MPa, representing approximately a 49% increase in UCS. The comparatively higher strength gain observed between 7 and 28 days at lower RMO content (i.e. 2%) suggests more

progressive and sustained carbonation, likely due to the favourable pH conditions that support prolonged bacterial metabolic activity. In contrast, at a higher RMO content (8%), the reduced relative strength gain may be attributed to elevated alkalinity, which limits further microbial activity and carbonation efficiency over time.

### 3.2 Impact of Urease Activity on UCS

Figure 3 depicts the effect of varying the activity of the urease-producing bacteria on the carbonation of CRB with 2% RMO and 1.0 M urea concentration. The activity of the urease-producing bacteria was varied as 8.67 U/mL and 16.45 U/mL. The UCS test result indicated increased peak strength values with higher urease activity, irrespective of the designated curing time. Specifically, the UCS values increased by approximately 42% and 40% at curing times of 7 and 28 days, respectively. This enhancement can be attributed to the accelerated hydrolysis of urea at higher enzyme activity, which promotes the more rapid generation of carbonate ions. The consistent strength improvement observed across different curing times indicates that the early-stage carbonate formation, driven by high urease activity, plays a critical role in the geomechanical performance of the RMO-treated CRB.

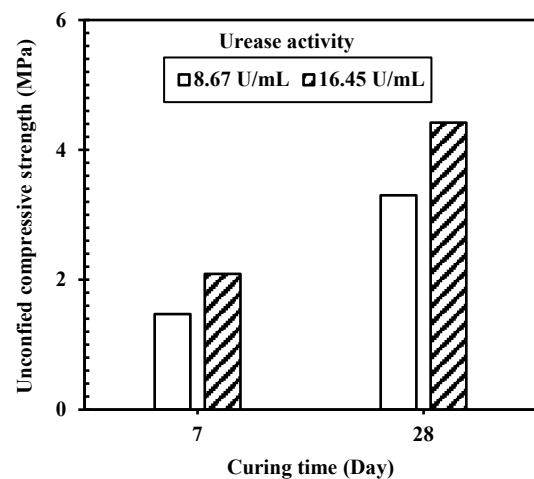


Figure 3. Unconfined Compressive Strength (UCS) of Crushed Rock Base (CRB) material treated with 2% Reactive Magnesium Oxide (RMO) and 1.0 M urea with varying urease activity after 7 and 28 days of curing.

### 3.3 Impact of Dust Ratio (DR) on UCS

Figure 4 illustrates the influence of DR on UCS of CRB material treated with 2% RMO and 1.0 M urea after 7 and 28 days of curing. In this study, the particle size distribution of the CRB was deliberately modified to increase the proportion of particles retained on the 75-micron sieve. This adjustment resulted in a decrease in the DR of 0.38 for the modified gradation. The results indicate that increasing the amount of 75-micron fine particles in the CRB mix led to approximately 8% and 9% increases in the UCS values at 7 and 28 days, respectively. This enhancement in strength may be attributed to the increased surface area provided by the finer particles, which likely improved the particle packing density and reduced void spaces within the matrix.

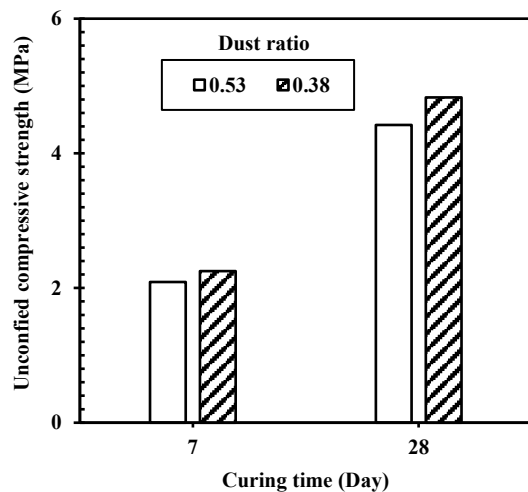


Figure 4. Unconfined compressive strength (UCS) of crushed rock base (CRB) material treated with 2% Reactive Magnesium Oxide (RMO) and 1.0 M urea with varying dust ratios after 7 and 28 days of curing.

#### 4 CONCLUSIONS

This study explored the feasibility of employing Microbial-Induced Hydrated Magnesium Carbonation (MIHMC) to stabilise crushed rock base (CRB) used for road construction. The study aimed to examine the effect of different Reactive Magnesium Oxide (RMO) contents, urea concentrations, curing times, and dust ratios (DR) on the UCS values of the MIHMC-treated CRB material. The following conclusions can be drawn from the findings of this study:

- Increasing the urea concentration enhances the UCS of MIHMC-treated CRB at a constant RMO content, primarily due to increased carbonate ion availability, which facilitates greater RMO carbonation and improves matrix bonding.
- Curing time significantly influences the strength development of MIHMC-treated CRB, with all mixtures exhibiting UCS gains between 7 and 28 days.
- Lower RMO content may facilitate more sustained microbial activity and progressive carbonation over time, resulting in greater relative strength gains during the curing process.
- Increasing urease activity significantly enhanced the UCS of MIHMC-treated CRB by up to 42%, highlighting the critical role of early-stage carbonate formation in strength development.
- Incorporating a higher proportion of 75-micron particles into the CRB mix (DR = 0.38) resulted in a 9% increase in UCS values at 28 days of curing, likely due to enhanced particle packing density and reduced pore spaces, which promote matrix densification.
- According to Austroads (2019) guidelines, a stabilised road base can be categorised into three types of cemented materials, including modified (UCS < 1.0 MPa), lightly bound (1.0 MPa ≤ UCS ≤ 2.0 MPa), and bound (UCS > 2.0 MPa). Based on the results obtained from the current study, the UCS of MIHMC-treated CRB samples is commensurate with the Austroads requirements for the bound road base material. A comparison of UCS values between MIHMC-treated CRB and CRB stabilised with 2–3% Ordinary Portland Cement (OPC), as reported by Shahin et al. (2024), revealed that the MIHMC-treated

CRB samples achieved equal or higher strength than those treated with OPC-treated CRB samples. This underscores the potential of MIHMC-based cementation in achieving results comparable to or higher than those of OPC-based cementation for bound CRB, while offering added advantages by mitigating the environmental impact and shrinkage-related issues typically associated with OPC hydration.

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