# Improvement of Shear Strength of Recycled Concrete Aggregate with MICP Treatment

**Rujira Pholtrai[1,*] Nutthachai Prongmanee[2] Amorndech Noulmanee[3] and Thawatchai Suppaso[4]**

*[1,2,3,4] Department of Science and Engineering, Faculty of Science and Engineering, Kasetsart University Chalermphrakiat Sakon Nakhon Province Campus, THAILAND*

**Corresponding author; E-mail address: rujira.pho@ku.th*

## Abstract

The increasing demand for sustainable construction materials has heightened interest in recycled concrete aggregate (RCA) as an alternative to natural crushed rock. However, RCA's broader adoption in geotechnical applications remains limited by concerns about its mechanical properties, particularly shear strength and stability. This study assesses the shear strength and compaction characteristics of untreated RCA, MICP-treated RCA, and conventional crushed rock using a large-scale direct shear test with a 15 cm diameter circular shear box. Microbially Induced Calcite Precipitation (MICP) enhanced interparticle bonding and shear resistance. Under varying normal stresses, parameters including peak and residual shear strength, cohesion (c), internal friction angle ($\phi$), and maximum dry density ($\gamma_{d, max}$) were evaluated. Results indicate that untreated RCA exhibits lower shear strength than MICP-treated RCA, primarily due to residual cement paste and weaker particle interlocking. Conversely, MICP treatment significantly improves RCA's cohesion and peak shear strength, confirming its potential as a sustainable replacement for natural aggregates. Despite a slight reduction in friction angle and maximum dry density due to altered particle packing efficiency from calcium carbonate ($CaCO_3$) precipitation, MICP-treated RCA displayed enhanced resistance to post-peak strength loss, resulting in consistently higher residual shear strength. Therefore, the bio-stabilization provided by MICP emerges as a promising, environmentally friendly alternative to traditional chemical stabilizers, supporting the reuse of construction waste materials. Further optimization to balance cohesion gains with frictional properties is recommended to enhance the competitive performance of MICP-treated RCA against natural aggregates. This call for further optimization challenges the audience, encouraging them to contribute to the advancement of eco-friendly soil stabilization methods and the promotion of circular economy practices in the construction industry.

Keywords: Recycled concrete aggregate (RCA), Microbially induced calcite precipitation (MICP), Shear strength, Large-scale direct shear test, Sustainable geomaterials

## 1. Introduction

The increasing demand for sustainable construction materials has led to the widespread adoption of recycled concrete aggregate (RCA) as an alternative to natural aggregates. RCA is derived from construction and demolition waste, offering a sustainable solution to resource depletion and waste management challenges. Using RCA in concrete supports the circular economy by reducing waste and emissions and provides a viable alternative to natural aggregates, which are becoming scarce due to over-extraction. The following sections explore the feasibility, benefits, and challenges of using RCA in construction [1]. RCA, derived from demolished concrete structures, offers an eco-friendly solution for reducing construction waste and minimizing the depletion of natural resources [2]. However, RCA exhibits lower shear strength and weaker interparticle bonding than conventional aggregates due to residual mortar, higher porosity, and reduced particle integrity. These factors limit its structural applications, particularly in geotechnical engineering and pavement construction [3].

Recent advancements in bio-geotechnical engineering have explored the potential of using Microbially Induced Calcite Precipitation (MICP) as a stabilization technique to address the limitations of recycled concrete aggregate (RCA). MICP, a biologically driven process in which bacteria facilitate calcium carbonate ($CaCO_3$) precipitation, has shown promising results in improving mechanical properties such as cohesion, friction angle, and overall shear resistance. This method, with its potential to revolutionize soil stabilization, self-healing concrete, and bio-cementation applications, offers a bright future for sustainable construction. Previous research on cementitious stabilization and permeability characteristics of recycled and stabilized materials has emphasized optimizing grain size distribution and controlling water content for structural applications. Additionally, studies on microbial calcite production have demonstrated its feasibility for soil stabilization and pavement recycling applications. However, there are limitations to using MICP-treated RCA in road construction.

This study investigates the effectiveness of MICP treatment in enhancing the shear strength of RCA. The experimental program involves treating RCA with 4M $CaCl_2$ and 4M $(NH_4)_2CO_3$ solutions, compacting the treated material into a 150 mm diameter circular direct shear mold, and curing it for 7 days before testing. The treated RCA's shear behavior is compared to untreated RCA under identical test conditions. Key parameters such as peak and residual shear strength, friction angle, and cohesion are analyzed to assess the influence of MICP treatment on RCA's mechanical performance. By integrating these concepts, this research aims to develop an eco-friendly and structurally improved RCA stabilization method using MICP. The audience, as academic researchers and professionals in sustainable construction and geotechnical engineering, play a crucial role in further optimizing MICP treatment to enhance the competitive performance of MICP-treated RCA against natural aggregates. By demonstrating the potential of bio-stabilization techniques, this research can contribute to developing sustainable construction practices while addressing challenges associated with RCA's shear strength, durability, and microstructural stability.

## 2. Materials and methods

### *2.1 Recycled Concrete Aggregate (RCA)*

The recycled concrete aggregate (RCA) used in this study was obtained from crushed 15×15×15 cm concrete cube specimens collected after compressive strength testing at Kasetsart University Chalermphrakiat Sakon Nakhon Province Campus, Sakon Nakhon, Thailand, with an average compressive strength of 27.5 ± 10 MPa. The RCA was processed by sieving to achieve a well-graded particle size distribution following DOH 201/2544 for road base construction. The water absorption of the RCA was measured at 5.75%, while the Los Angeles (LA) abrasion loss was recorded at 38.5%, indicating moderate durability. The Modified Proctor compaction test determined the maximum dry density (MDD) and optimum moisture content (OMC). The gradation curve of the processed RCA is shown in Fig. 1, comparing its particle size distribution with the standard gradation required by the Department of Highways (DOH) Thailand for road-based applications, ensuring compliance with infrastructure specifications. The gradation curve of RCA before and after compaction, as shown in Fig. 1, illustrates the particle size distribution changes due to compaction. After compaction, a noticeable shift towards finer particle sizes is observed, indicating particle breakage and densification during compaction. This behavior is expected, as recycled concrete aggregates tend to experience particle crushing due to their residual mortar content, which weakens under loading. The comparison with DOH standard limits confirms that the untreated and compacted RCA samples remain within acceptable gradation specifications, supporting their feasibility for pavement and subbase applications.

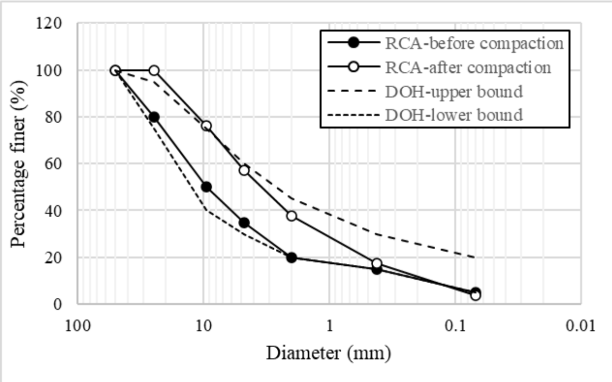


**Fig. 1** RCA gradation curve before and after compaction compared with DOH standard

### *2.2 Chemical Reagents for MICP Treatment*

The Microbially Induced Calcite Precipitation (MICP) treatment was conducted following the method described by [4]. This approach involves the in-situ precipitation of calcium carbonate ($CaCO_3$) through a controlled reaction between calcium chloride ($CaCl_2$) and ammonium carbonate ($(NH_4)_2CO_3$) solutions derived from a bioprocess. The two solutions were pre-mixed in equal proportions and applied to the RCA to induce $CaCO_3$ precipitation as a binding agent. The total solution volume was adjusted to 486.73 mL, corresponding to 9 % of RCA's dry mass, ensuring uniform treatment while maintaining compaction requirements.

*2.3 Compaction test*

The compaction characteristics of recycled concrete aggregate (RCA) were determined using the Modified Proctor Compaction Test following ASTM D1557. This test was conducted to establish RCA's optimum moisture content (OMC) and maximum dry density (MDD). For the MICP-treated RCA, a pre-mixed solution containing 4M $CaCl_2$ and 4M $(NH_4)_2CO_3$ was incorporated during sample preparation. The moisture content used for the MICP treatment was set to match the optimum water content (OMC) obtained from the untreated RCA to ensure consistency in compaction conditions and allow for a direct comparison of the effects of MICP treatment on compaction behavior.

*2.4 Direct Shear Test Method*

The shear strength of untreated and MICP-treated RCA was evaluated using a custom-developed large-scale direct shear apparatus with a 150 mm circular shear mold designed to accommodate coarse aggregate materials. The test was conducted following ASTM D3080 under drained conditions, with specimens compacted at optimum moisture content and maximum dry density. Normal stresses of 20, 40, and 80 kPa were applied, and shearing was performed at a controlled shear rate of 0.5 mm/min, selected based on RCA permeability and particle size. Two load cells were installed in the apparatus: a 20-ton load cell for measuring the horizontal shear force and a 30-ton load cell for controlling the vertical normal stress. Horizontal displacement was measured using a 100-mm LVDT. Both load cells and the LVDT were connected to a Kyowa UCAM-60A data logger. Shear stress and displacement data were recorded to determine peak and residual shear strength, from which cohesion (c) and friction angle ($\phi$) were calculated using Mohr-Coulomb failure envelopes. Note that this research does not investigate the dilatancy effect during the shearing test; therefore, this study did not install vertical displacement measurements.

## 3. Results and Discussion

The compaction test results, as shown in Fig. 2, indicate that while both untreated and MICP-treated RCA were compacted at an optimum moisture content (OMC) of 9%, the maximum dry density (MDD) of MICP-treated RCA was 1.775 t/m3, which is slightly lower than that of untreated RCA of 1.83 t/m3. This unexpected reduction in density can be attributed to $CaCO_3$ precipitation altering particle packing efficiency, increasing interparticle friction, and introducing microstructural voids that hinder compaction. Instead of densifying the RCA structure, the MICP process led to the formation of surface coatings and weak bonds between particles, which may have contributed to lower packing efficiency compared to untreated RCA. These findings align with previous studies on bio-cemented materials, where $CaCO_3$ precipitation alters compaction behavior but contributes to strength enhancement over time [5].

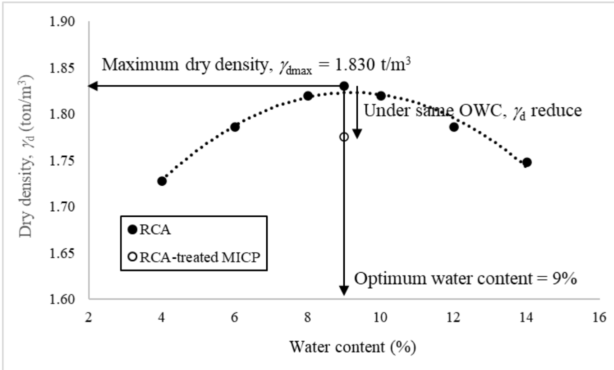


**Fig. 2** Compaction Characteristics of MICP-Treated and Untreated RCA

The shearing behavior of untreated and MICP-treated RCA, as illustrated in Fig. 3, reveals significant differences in both peak and residual shear strength, highlighting the effectiveness of MICP treatment in enhancing the mechanical performance of RCA. The untreated RCA samples exhibited a lower peak shear stress, followed by a rapid decline in post-peak strength, characteristic of particle slippage, dilation, and crushing under shear loading. This behavior suggests that untreated RCA relies primarily on interparticle friction. Once the peak strength is reached, the structure loses stability, leading to a notable drop in residual shear strength. In contrast, the MICP-treated RCA samples demonstrated a higher peak shear strength, indicating that $CaCO_3$ precipitation effectively enhanced interparticle bonding, thereby increasing cohesion and overall shear resistance. The shear stress–displacement curves for treated RCA showed a more gradual strength loss after peak stress, suggesting that carbonate bonding reduced excessive dilation and particle rearrangement, which typically contribute to a sudden decrease in shear strength in untreated samples. Furthermore, the residual shear strength of MICP-treated RCA remained significantly higher than that of untreated RCA, confirming that $CaCO_3$ precipitation provided long-term structural stability, preventing significant reductions in shear resistance during prolonged deformation.

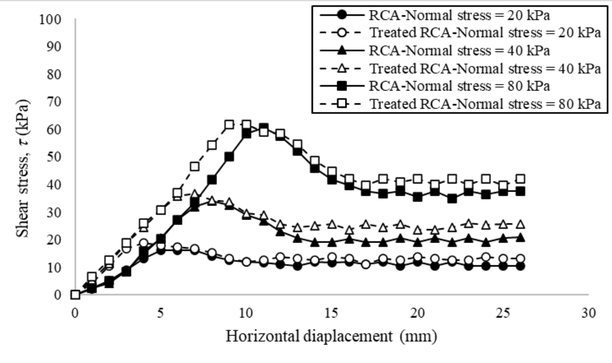


**Fig. 3** Shear-displacement behavior of MICP-treated and untreated RCA

The improvements in shear strength behavior can be attributed to multiple mechanisms induced by MICP treatment, including the formation of calcite bridges that increase cohesion, microstructural changes that reduce excessive dilation, and enhanced particle interlocking due to carbonate-induced surface roughness. These effects collectively contribute to a more stable shear response, making MICP-treated RCA a promising material for geotechnical applications such as road base layers, subgrade stabilization, and embankment construction, where high shear strength and durability are critical. Moreover, the differences in the shear behavior of treated and untreated RCA align with previous findings in bio-cemented materials, where shear resistance improvements are more pronounced at lower normal stresses due to the increased contribution of cohesive bonding. As normal stress increases, the frictional component dominates, but $CaCO_3$ bonding still significantly improves residual strength, reducing strength degradation over time. These findings emphasize the potential of MICP treatment in mitigating the limitations of RCA, offering a sustainable approach to enhancing shear performance without relying on traditional cement-based stabilization techniques.

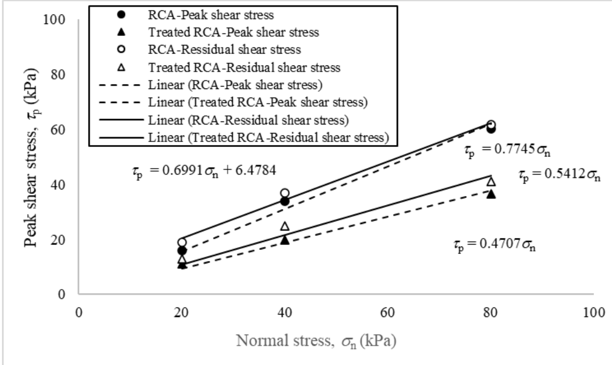


**Fig. 4** Summary of Mohr-Coulomb Failure Envelope for MICP-Treated and Untreated RCA.

Fig. 4 presents the Mohr-Coulomb failure envelopes for both peak and residual shear strength of untreated and MICP-treated RCA under different normal stress conditions (20, 40, and 80 kPa), illustrating the influence of $CaCO_3$ precipitation on shear behavior. The trendlines indicate that untreated RCA exhibits a steeper failure envelope, suggesting a higher friction angle ($\phi$), as its shear strength primarily depends on particle interlocking and frictional resistance between aggregates. In contrast, MICP-treated RCA demonstrates a slightly lower slope, indicating a moderate reduction in friction angle due to $CaCO_3$ precipitation smoothing particle surfaces, reducing interparticle roughness, and altering direct aggregate-to-aggregate contact. However, the interception of the failure envelope is notably higher for MICP-treated RCA, signifying a substantial increase in cohesion (c), which results from calcite bonding between particles, enhancing resistance to shear forces at lower normal stresses. Furthermore, after reaching peak shear strength, untreated RCA experiences a sharp drop in strength due to particle degradation and rearrangement, leading to a significant reduction in residual strength.

In contrast, MICP-treated RCA retains a higher residual shear strength, suggesting that bio-cementation mitigates strength loss by maintaining structural integrity and reducing particle crushing during shear deformation. The residual failure envelope for MICP-treated RCA remains above that of untreated RCA, confirming that $CaCO_3$ bonding enhances long-term stability by limiting post-peak degradation. Overall, while untreated RCA provides higher peak frictional resistance due to stronger particle interlocking, MICP-treated RCA benefits from increased cohesion, improved residual strength, and a more stable shear response, making it suitable for applications where sustained load resistance and reduced strength loss are critical, such as road bases, retaining walls, and embankment stabilization. Although the MICP-treated RCA significantly improved shear strength, its shear parameters remained lower than virgin crushed rock, which exhibited a friction angle of 44° [6]. Therefore, this study recommends using RCA as a replacement for natural crushed rock in combination with MICP treatment rather than using pure RCA alone for road base construction. It is important to highlight that the cohesion (c) resulting from microbial-induced calcite precipitation (MICP) is highly dependent on the stages of deformation and the characteristics of the aggregate. At peak shear strength, the cementation effect provided by MICP significantly enhances cohesion. However, as shear deformation continues into larger strains beyond this peak, the calcite bonding bridges may break down. At this point, the aggregate particles primarily rely on frictional interactions, which can significantly reduce or even eliminate the cohesion component. Therefore, the increase in cohesion due to MICP treatment is most effective at lower strains associated with peak shear strength, rather than at larger strains that correspond to residual shear conditions. This is particularly relevant for coarse-grained aggregates like recycled concrete aggregate (RCA).

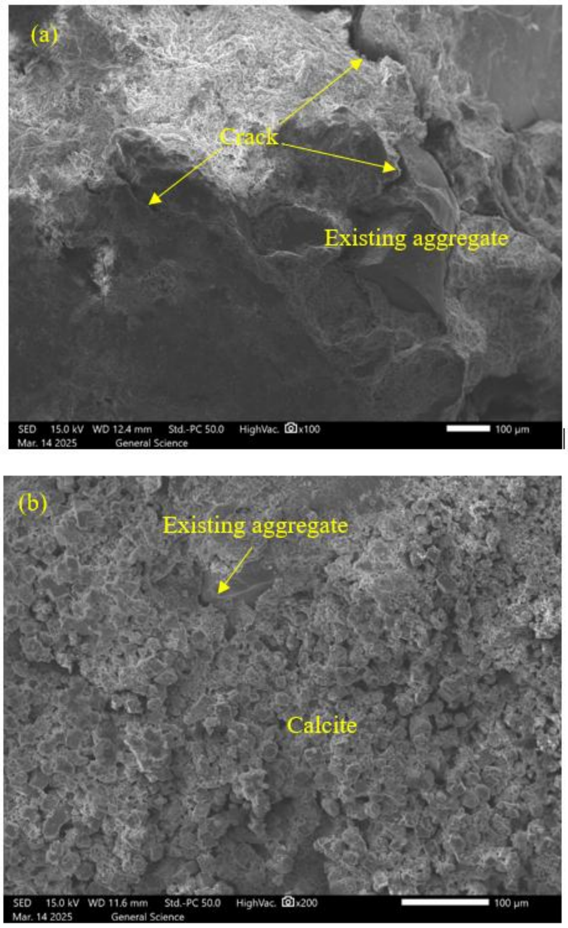


**Fig. 5** SEM images of (a) RCA and (b) MICP-treated RCA

The scanning electron microscopy (SEM) analysis of untreated and MICP-treated RCA reveals distinct microstructural differences that explain the observed variations in shear strength and compaction behavior. The untreated RCA exhibits a highly porous and rough surface with irregular, fractured particles, indicating that its shear strength primarily relies on particle interlocking and friction rather than cohesive bonding. Micro-cracks and loosely packed aggregates suggest the untreated RCA is more susceptible to crushing and strength loss under repeated loading, consistent with its lower residual shear strength observed in direct shear tests. In contrast, the MICP-treated RCA shows a more compact and structured micro-texture, with visible $CaCO_3$ precipitation forming well-defined calcite bridges between particles. These carbonate bonds enhance cohesion, leading to more excellent resistance to shear forces and improved residual strength. The rhombohedral and cubic calcite crystals observed in the SEM image confirm successful microbial precipitation, which helps stabilize the RCA structure by reducing micro-cracking and minimizing particle displacement during shear deformation. This explains the higher cohesion (c) values and improved residual shear strength seen in treated samples despite a slight reduction in the friction angle ($\phi$), which can be attributed to the smoother particle surfaces resulting from carbonate coating. The microstructural changes introduced by MICP treatment not only enhance interparticle bonding but also reduce the extent of particle degradation, making MICP-treated RCA more suitable for long-term applications in road-based construction. While well-graded crushed rock typically relies on high friction and particle interlocking for strength, MICP-treated RCA compensates for its lower friction angle by gaining additional cohesion through bio-cementation, making it less prone to excessive deformation under cyclic loading. These findings reinforce the potential of MICP as a sustainable stabilization method for RCA, offering an alternative to chemical stabilizers such as cement or lime while reducing environmental impact and material costs. Further research on extended curing times and field-scale performance will provide deeper insights into how bio-cemented RCA behaves under long-term traffic loads and environmental exposure, ensuring its feasibility as a durable and eco-friendly alternative for pavement and geotechnical applications.

## 4. Conclusion

This study investigated the shear strength behavior and compaction characteristics of MICP-treated RCA, evaluating its potential as a sustainable road-based material. The results demonstrated that MICP treatment improved cohesion (c) and residual shear strength while causing a slight reduction in friction angle ($\phi$) and maximum dry density ($\gamma_{d, max}$) compared to untreated RCA. The lower $\gamma_{d, max}$ observed in the compaction tests suggests that $CaCO_3$ precipitation altered the packing efficiency of RCA, limiting densification. However, despite this reduction, MICP-treated RCA exhibited more excellent resistance to post-peak strength loss, maintaining higher residual shear strength than untreated RCA. The bio-stabilization effect of MICP provides a promising alternative to chemical stabilizers, reducing environmental impact and promoting the reuse of construction waste materials. However, further optimization is needed to balance cohesion gain and frictional performance to enhance its competitiveness with natural aggregates.

## Acknowledgement

The authors thank the Faculty of Science and Engineering, Kasetsart University Chalerm Phrakiat Sakon Nakhon Campus, for providing space and equipment for apparatus testing and the undergraduate students for their valuable contributions and assistance throughout this research project. Their dedication and support in conducting experiments and analyzing data have been instrumental in achieving the study's objectives. Additionally, the authors acknowledge that this research was financially supported by the Center of Excellence in Research and Technology (CETAR).

## References

[1] Bardan, M., & Czarnecki, L. (2025). Green Recycled Aggregate in Concrete: Feasibility Study. Materials, 18(3), 488.

[2] Los Santos-Ortega, J., Fraile-García, E., & Ferreiro-Cabello, J. (2024). Environmental and economic viability of using concrete Block Wastes from a concrete production plant as recycled Coarse aggregates. Materials, 17(7), 1560.

[3] Noulmanee, A., & Prongmanee, N. (2021). Compressive strengths of pavement recycling materials and new approach for cement content determination. Civil and Environmental Engineering, 17(1), 335–342.

[4] Prongmanee, N., Horpibulsuk, S., Dulyasucharit, R., Ousmane, A., et al. (2023). Novel and simplified method of producing microbial calcite powder for clayey soil stabilization. Geomechanics for Energy and the Environment, 35, 100480.

[5] Ali, M. S., & Almurshedi, A. D. (2024). Bio-cementations: A Review on Enzyme and Microbially Induced Calcite Precipitation Mechanisms and Applications in Geotechnical Engineering. Journal of Engineering, 30(12), 167–188.

[6] Saberian, M., Li, J., Perera, S. T. A. M., Zhou, A., Roychand, R., & Ren, G. (2021). Large-scale direct shear testing of waste crushed rock reinforced with waste rubber as pavement base/subbase materials. Transportation Geotechnics, 28, 100546.