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Enhancement of Residual Shear Strength and Reduction of Strength Degradation in Low-Plasticity Clay Using Biostimulated MICP

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ABSTRACT

Low-plasticity tropical clays typically exhibit low residual shear strength due to kaolinite dominated mineralogy and intense weathering, highlighting the need for stabilization methods capable of improving strength beyond the peak condition. The novelty of this study lies in the specific application of biostimulated MICP to enhance residual shear stress and reduce the degradation of friction angle and cohesion in CL soils an aspect that is still limited explored in previous MICP research. The Direct Shear Test was employed to evaluate changes in shear behavior following the activation of indigenous bacteria, which promote $CaCO_3$ precipitation along the shear plane. The results demonstrate that biostimulated MICP significantly increases residual shear strength through the formation of mineral bonds that preserve interparticle linkage, while simultaneously reducing the degradation from peak to residual states. Residual strength improved consistently across all normal stress levels, and both friction angle and cohesion exhibited lower degradation compared with untreated samples, confirming the effectiveness of $CaCO_3$ precipitation as a post-peak reinforcement mechanism. These findings indicate that biostimulated MICP is a sustainable and efficient approach for enhancing the long-term stability of tropical clay soils.

Keywords: MICP, biostimulation, residual strength, shear stress, degradation.

INTRODUCTION

Low-plasticity clay (CL) in tropical regions of Indonesia exhibits a low residual shear strength of approximately 11.8 kPa [1], representing the shear resistance mobilized after the soil surpasses its peak strength [2]. This low value is influenced by intense weathering and the dominance of kaolinite minerals, which possess weak interparticle bonding [3]. High rainfall and repeated wet-dry cycles further degrade the soil's microstructure, leading to a reduction in shear resistance [4]. Field investigations in Brazil have shown that such low residual shear strength facilitates soil mass movement and increases landslide susceptibility under humid climatic conditions [5]. Therefore, residual shear strength is a critical parameter for evaluating the long-term stability of clayey slopes in tropical environments [6].

Conventional stabilization methods such as cement addition can increase the initial strength of soil [7]. However, the chemical bonds formed are highly susceptible to degradation caused by moisture fluctuations and repeated deformation cycles, limiting their ability to maintain residual strength [8]. As an alternative, MICP utilizes microbial activity to generate calcium carbonate ($CaCO_3$) precipitates between soil particles [9]. The MICP mechanism involves urea hydrolysis by urease enzymes, producing CO_3^{2-} and NH_4^+, which subsequently react with Ca^{2+} to form $CaCO_3$ as a natural interparticle cementing agent [10]. Two main approaches are employed in MICP, bioaugmentation and biostimulation. Bioaugmentation introduces external bacteria such as *Sporosarcina pasteurii*, but its effectiveness is still limited because foreign bacteria often struggle to adapt and distribute uniformly within the soil matrix [11]. In contrast, biostimulation activates indigenous bacteria by supplying nutrients such as urea and $CaCl_2$, thereby enhancing natural urease activity and promoting more uniform and stable $CaCO_3$ formation [12]. The resulting $CaCO_3$ enhances the shear plane, increases interparticle cohesion, and helps maintain post-peak strength, making biostimulated MICP more efficient and environmentally sustainable than conventional chemical stabilization methods.

Shear strength improvement has been widely observed across various soil types treated using both biological and chemical stabilization methods. In well-graded medium sand (SP-SM), increases of 30-67% in peak shear strength, 4-18.8% in residual shear strength, up to 190% in cohesion, and 16.8% in internal friction angle have been reported [12]. In sand-bentonite mixtures (SW-CL), local ureolytic activity increased, accompanied by the formation of large $CaCO_3$ crystals that reinforced the soil microstructure [13]. For high plasticity expansive clay (CH), cohesion increased by 34% and the internal friction angle by 47%, along with a more stable strain hardening response [14]. In another study using expansive clay, the addition of nano-SiO_2 was also found to increase shear strength by up to 64% [15]. Undrained shear strength improvements of up to 148% have also been documented in high-plasticity marine clay (MH-CH) [16], while fractured sandstone exhibited a 26-40% increase in peak shear stress and up to a 70% increase in shear stiffness after fracture voids were filled with $CaCO_3$ precipitates [17]. As a comparison, cement-treated kaolinitic clay (CL) showed residual shear strength increases of 53% at a normal stress of 98 kPa, 31% at 196 kPa, and 16% at 294 kPa due to the formation of interparticle cementation bonds [7]. Additionally, in remolded clay (CL), the addition of 8% lime increased the residual friction angle by 80%, while a combination of 4% lime and 0.3% polypropylene fiber enhanced it by up to 100%, demonstrating the synergistic interaction between chemical bonding and mechanical fiber interlocking [18]. Overall, both biological (biostimulation and bioaugmentation) and chemical approaches (cement, lime, and fiber reinforcement) have been proven effective in enhancing cohesion and residual friction angle through the formation of new microstructural bonds that slow the degradation of strength from peak to residual conditions.

Although numerous studies have demonstrated the effectiveness of MICP in enhancing shear strength, most have focused on sandy soils and high-plasticity clays using bioaugmentation; however, applications of biostimulated MICP on low-plasticity clay (CL) with an emphasis on residual shear strength remain still limited. This study aims to evaluate the influence of biostimulated MICP on the residual shear strength of low-plasticity clay (CL). In addition, the degradation of shear strength from peak to residual conditions is examined. Direct Shear Tests were conducted to determine the changes in cohesion and internal friction angle resulting from MICP treatment. The findings are expected to show that the activation of indigenous bacteria through biostimulated MICP can promote $CaCO_3$ precipitation along the shear plane, thereby increasing residual shear strength and reducing the rate of strength degradation from peak to residual conditions in low-plasticity clay (CL).

RESEARCH METHODS

Materials

The soil used in this study was collected from the Universitas Kadiri campus area at a depth of approximately ±80 cm to obtain undisturbed soil conditions [19], [20]. After sampling, the soil was air-dried for about two weeks at room temperature in a shaded environment to protect it from direct sunlight, allowing the moisture content to reach approximately ±10% to maintain the activity of indigenous bacteria [21]. The dried soil was then pulverized and sieved using a 0.3 mm mesh. Based on the Unified Soil Classification System (USCS), the soil is classified as low-plasticity clay (CL), consisting of 31.45% sand, 52.39% silt, and 16.17% clay. The Atterberg limit tests yielded a liquid limit (LL) of 24.99%, a plastic limit (PL) of 10.93%, and a plasticity index (PI) of 14.06%.

MICP Solution

The MICP solution was prepared by mixing several chemical components, including 0.333 mol/L urea [22], 0.3 mol/L $CaCl_2$, 0.1 mol/L CH_3COONa, 0.001 mol/L NaOH [23], and 3 g/L sugarcane molasses [24]. Each component was weighed according to the specified concentration, dissolved in distilled water, and stirred until fully homogenized. Once the solution became uniform, it was used immediately to prevent degradation or loss of effectiveness of the active constituents.

Samples

This study employed two treatment conditions, samples prepared with ordinary water and samples treated with the MICP solution. The sample mold had a height of 2 cm and a diameter of 6.3 cm [25]. The wet unit weight of the soil was maintained at 1.61 g/cm³, with water or MICP solution

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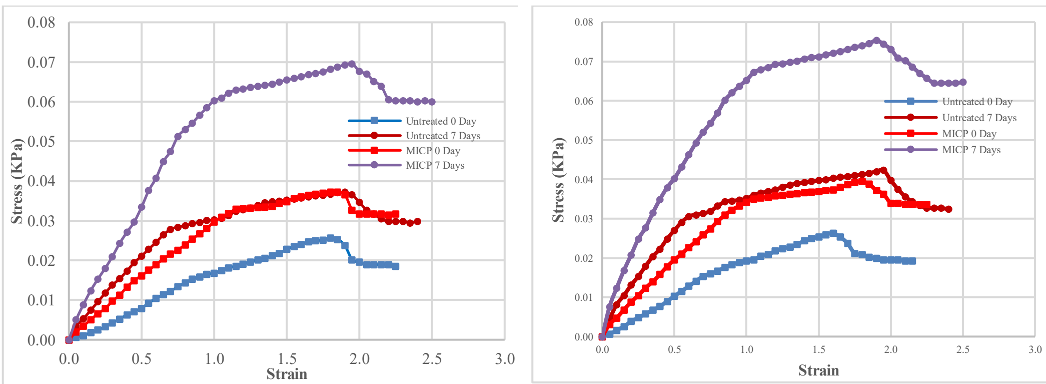
added at 40% of the soil weight. The inner walls of the mold were lined with wax paper to prevent soil adhesion and facilitate sample removal after compaction. Sample preparation was carried out using the air pluviation method to ensure uniform particle distribution and produce a homogeneous specimen [26]. After the mold was filled, the surface of the sample was leveled using a brush, followed by the application of the solution at the predetermined unit weight, and allowed to stand for approximately two minutes to ensure complete infiltration. Once the infiltration process was completed, the sample was carefully removed from the mold and wrapped with plastic film to maintain moisture and temperature stability during incubation. Each treatment variation was prepared in triplicate to ensure data reliability and accuracy. The samples were then incubated for 0 and 7 days at room temperature without direct exposure to sunlight. The chosen incubation period reflects the typical timeframe in which calcium carbonate ($CaCO_3$) precipitation begins to occur significantly [24].

Data Analysis

The Direct Shear Test was conducted in accordance with D3080/D3080M-23 [27], using three levels of normal stress 1.097 kPa, 3.125 kPa, and 4.025 kPa and a constant shear rate of 0.1 mm/s. Load data were recorded using a calibrated load cell[28], while vertical deformation was measured with a linear potentiometer [29], and all measurements were automatically logged using Excel Data Streamer [30]. The test results were analyzed in the form of shear load–deformation curves to compare the behavior of untreated and MICP-treated samples, which were subsequently converted into shear stress-strain curves. The internal friction angle (ϕ) and cohesion (c) were determined based on the Mohr-Coulomb failure criterion, which defines the linear relationship between shear stress and normal stress on the failure plane [31]. Residual shear stress in this study was determined following the approach recommended in [2], in which the residual value is obtained at large displacement after all interparticle bonds have been eliminated, leaving the soil strength governed solely by particle-to-particle friction along the shear plane. Statistical analysis was performed using a one-way ANOVA to compare the mean degradation and residual values between untreated and MICP-treated samples at each incubation period, using a 95% confidence level ($\alpha = 0.05$) [32].

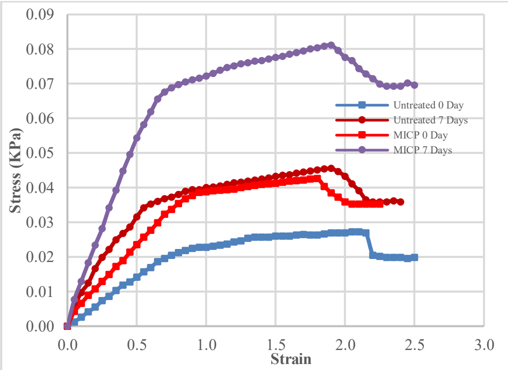
RESULT AND DISCUSSION

Stress-Strain Relationship



a. Stress-Strain Behavior at a Normal Stress of 1,097 kPa

b. Stress-Strain Behavior at a Normal Stress of 3,125 kPa



c. Stress-Strain Behavior at a Normal Stress of 4,025 kPa

Figure 1. Stress-strain curves under normal stresses of (a) 1.097 kPa, (b) 3.125 kPa, and (c) 4.025 kPa.

The test results indicate that the stress-strain response of low-plasticity clay (CL) exhibits a progressive increase in shear capacity with MICP treatment and incubation. At a normal stress of 1.097 kPa, the stress at the end of the elastic phase increased by 139.3%, accompanied by a 50% increase in elastic strain. At 3.125 kPa, the elastic stress limit increased by 93.5% and the corresponding strain by 41.7%, while at 4.025 kPa the elastic stress limit rose by 94.1% with an 18.2% increase in strain. The rightward shift of the curves toward higher stress levels and the extension of the elastic phase indicate enhanced internal stiffness due to $CaCO_3$ precipitation, which reinforces interparticle bonding and reduces microscale deformation. This mechanism aligns with findings that report up to a 70% increase in shear stiffness in porous rock after $CaCO_3$ filled fractures [17], as well as studies on high-plasticity marine clay showing a transition toward more elastic behavior following MICP treatment [16]. The results of this study are consistent with these trends, demonstrating that biostimulated MICP promotes microstructural strengthening and shifts the shear response toward stiffer, more stable, and deformation-resistant behavior.

Relationship Between Shear Stress and Normal Stress

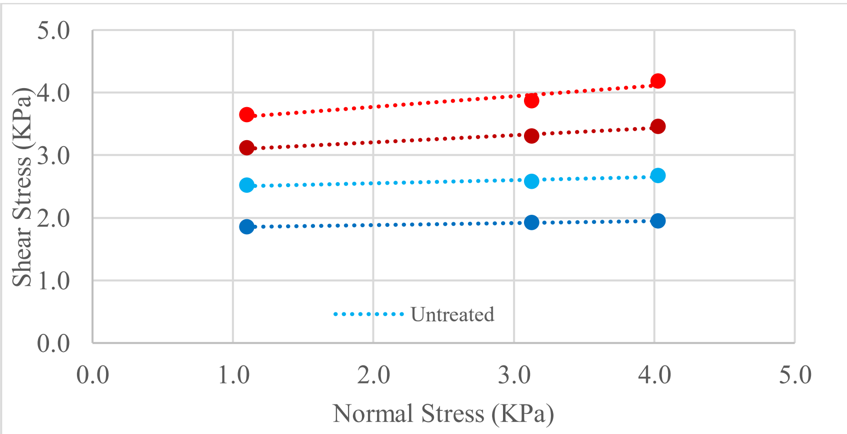


Figure 2. Trendlines Between Shear Stress and Normal Stress at 0 Day Incubation

The test results show that at 0 days of incubation, the linear relationship between normal stress and shear stress indicates an increase in soil strength after MICP treatment compared with untreated samples. Shear stress increased by 45-56%, while residual shear stress rose by 62-77%. These improvements are attributed to calcium carbonate ($CaCO_3$) precipitation generated by ureolytic bacterial activity, which strengthens interparticle contacts and reduces soil porosity. The carbonate precipitates act as natural cementing agents that enhance cohesion and extend the soil's elastic phase. These findings are consistent with studies reporting a 26-40% increase in shear stress in sandstone

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after fractures were filled with $CaCO_3$ [17], as well as significant shear strength gains in expansive soils with higher cementation-solution concentrations [14].

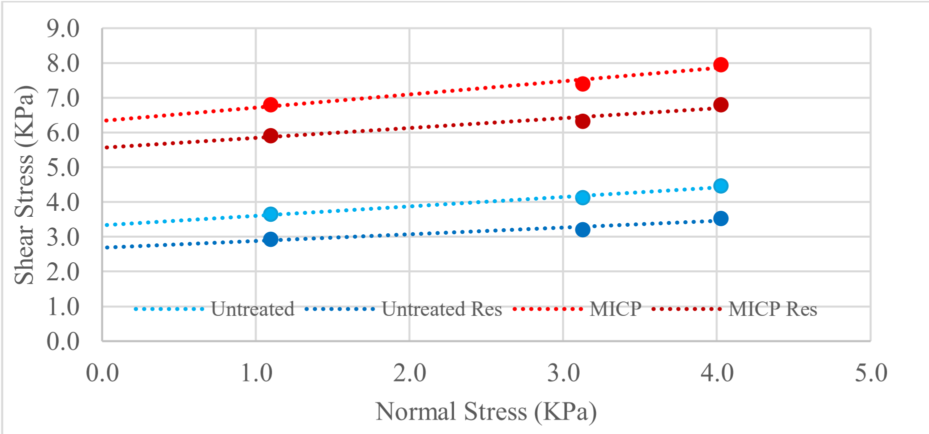
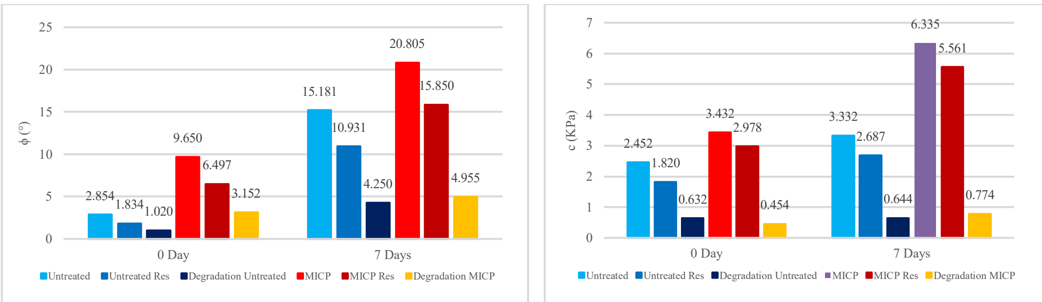


Figure 3. Trendlines Between Shear Stress and Normal Stress at 7 Days Incubation

After 7 days of incubation, the increase in soil strength becomes even more pronounced. Shear stress rises by 83-98%, while residual shear stress increases by 85-93% compared with untreated samples. This improvement indicates that precipitation processes continue during incubation, strengthening the soil matrix through a more uniform distribution of $CaCO_3$ along the shear plane. The precipitates act as interparticle bridges that enhance long-term deformation resistance. These findings are consistent with reports of approximately a 160% increase in peak shear strength in root soil composites following MICP treatment, demonstrating the effectiveness of biostimulation in reinforcing low-plasticity soils and improving their long-term stability [33].

Residual Parameters (φ_{res} and c_{res}) and Degradation



a. Comparison of Friction Angle, Residual Friction Angle, and Degradation Between Untreated and MICP-Treated Samples

b. Comparison of Cohesion, Residual Cohesion, and Degradation Between Untreated and MICP-Treated Samples

Figure 4. Comparison of Residual Parameters, (a) Friction Angle, Residual Friction Angle, and Degradation, (b) Cohesion, Residual Cohesion, and Degradation

Table 1. ANOVA Results for Degradation

Degradation	P-Value
ϕ 0 Day	0.12613777
c 0 Day	0.24737603
ϕ 7 Days	0.0378963
c 7 Days	0.00183239

The test results indicate a significant improvement in the shear strength parameters of the soil after MICP treatment and incubation. The residual friction angle (φ_{res}) increased by 45% after 7 days of treatment, while the residual cohesion (c_{res}) increased by 107%. These enhancements are attributed to the formation of $CaCO_3$ precipitates generated through biostimulation, which fill micropores, strengthen interparticle bonding, and stabilize the shear plane after large deformations; the calcite deposits act as mineral bridges that maintain shear resistance beyond the softening phase [14], [17]. Previous studies on lime-treated soils have also reported an 80% increase in residual friction angle [18]. however, lime stabilization produces high CO_2 emissions and involves chemical reactions that may be environmentally corrosive, making it less compatible with sustainable ground improvement practices. In contrast, biostimulation using sugarcane molasses as a carbon source has been shown to increase residual cohesion by 55-97% with higher molasses concentrations, due to the more homogeneous distribution of calcite along the shear plane [24]. These findings reinforce that biostimulated MICP is more environmentally friendly and effective in strengthening soil through natural $CaCO_3$ precipitation mechanisms without the need for external bacterial addition [11], [33].

The degradation analysis shows that for untreated samples at 0 days, the friction angle (φ) decreased by 36%, whereas in MICP-treated samples the reduction was slightly lower at 33%, with ANOVA indicating no significant difference ($p = 0.126$). For cohesion at 0 days, the reduction in the control sample was 31%, which decreased to 23% in the MICP-treated sample; however, this difference was also statistically insignificant ($p = 0.247$). After 7 days of incubation, all parameters exhibited significant improvements: friction-angle degradation decreased from 28% to 24% ($p = 0.037$), and cohesion degradation decreased from 24% to 18% ($p = 0.001$). These significant changes demonstrate that $CaCO_3$ precipitation formed during the biostimulation process strengthens the soil's microstructure, inhibits post failure structural weakening, and enhances deformation resistance in the residual phase [2], [7]. Comparative studies have similarly shown that calcite precipitation through MICP reduces plastic deformation and preserves residual strength under repeated loading cycles in well-graded sands [34]. Therefore, 7 days MICP treatment is proven to significantly enhance residual strength and reduce structural degradation, making it an efficient and sustainable stabilization method for tropical soils.

CONCLUSION

Biostimulated MICP was found to significantly enhance the residual shear strength of low-plasticity clay after 7 days of incubation. Peak shear stress increased by 45-56%, residual shear stress by 62-77%, while the residual friction angle (φres) and residual cohesion (cres) rose by 45% and 107%, respectively. In addition, biostimulation reduced friction-angle degradation from 28% to 24% and cohesion degradation from 24% to 18%. These findings indicate that $CaCO_3$ precipitates formed through the activation of indigenous bacteria effectively reinforce the shear plane, thereby not only improving residual shear strength but also suppressing the degradation of strength from peak to residual conditions in low-plasticity clay (CL). This study is limited by the absence of microstructural and chemical characterization of MICP-treated soil. Techniques such as Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) were not conducted, preventing detailed observation of the morphology, size, and distribution of $CaCO_3$ precipitates within the soil matrix. Future research is recommended to incorporate microstructural and chemical analyses to develop a deeper and more comprehensive understanding of the strengthening mechanisms induced by the MICP process.

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