Chinese Industry and Technology of Eco-environment
2025, VOL. 6, NO. 5, 45-49
DOI: 10.47297/wspciateWSP2633-772X09.20250605

Influence Mechanism and Application Research of MICP Technology on the Strength Characteristics of Ecologically Modified Soil

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ABSTRACT
Traditional rammed earth, as a time-honored building material, has certain application value, but its insufficient strength and poor durability restrict its widespread use in modern construction—these issues are particularly prominent under rainy and humid climatic conditions, making the modification of rammed earth imperative. In this study, we employ the Microbially Induced Calcite Precipitation (MICP) technology in combination with agricultural wastes to develop high-performance green rammed earth (straw-cattle manure soil). Specifically, we screen *Sporosarcina pasteurii* strains adapted to rainy and humid climates, optimize the medium formula to determine the optimal bacterial solution dosage, and systematically investigate the enhancement mechanism of the mechanical properties of rammed earth by integrating the synergistic effects of cattle manure, straw, glutinous rice slurry, and microorganisms. The results show that: cattle manure with a dosage of 10% directly enhances the soil strength; straw with a dosage of 5% yields the optimal strength performance of the green rammed earth; the incorporation of straw can alleviate internal stress concentration in the soil, while uneven mixing reduces its strength and stability.

KEYWORDS
Mechanical properties; Glutinous rice slurry; Cattle manure powder; Rice straw; MICP technology

1 Introduction

Rammed earth, as an ancient and sustainable construction method, has been extensively adopted in earth construction across rural areas of China—particularly in central and northwestern regions, where the arid climatic conditions and high-quality loess resources provide favorable prerequisites for the construction of rammed earth dwellings. Rammed earth boasts numerous advantages, including sustainability, thermal performance, and aesthetic appeal. However, its relatively inferior strength performance hinders its widespread application in modern construction. Thus, research on rammed earth modification technologies is particularly imperative. To improve the properties of rammed earth, scholars have conducted studies on soil modification by incorporating various additives. Prabakarden et al. [1] carried out experiments by adding plant fibers and found that sisal fiber can significantly enhance the compressive performance of soil; Hejazi S M et al. [2] reinforced soil structures using different fiber materials and successfully established prediction models to evaluate the performance changes of soil after fiber incorporation, with analysis indicating that the strength and stiffness of soil are effectively improved following fiber addition.

Microbially Induced Calcite Precipitation (MICP) technology, as an emerging biomineralization technology, has garnered extensive attention in the fields of geotechnical engineering and building material reinforcement in recent years [3-5]. This technology leverages specific microorganisms—such as *Sporosarcina pasteurii* based on the principle of urea hydrolysis—to achieve the reinforcement and restoration of soil, concrete, and cultural relics through their metabolic activities. Specifically, *Sporosarcina pasteurii* utilizes urea as a nutrient source; the bicarbonate ions (HCO_3^-) produced by urea decomposition combine with calcium ions (Ca^{2+}) in the environment to form cementitious calcium carbonate ($CaCO_3$) precipitates, which effectively cement loose sand particles and improve the overall strength and stability of the material.

As an organic material with excellent durability and good compatibility with ancient building substrates, glutinous rice slurry has attracted widespread attention in the field of cultural relic protection. Its application as a modified material in earthen site restoration can effectively enhance the restoration effect, making it a current research hotspot . Glutinous rice mortar—a formulation that incorporates glutinous rice slurry into inorganic materials—represents a major innovation in the history of ancient Chinese architecture, embodying the application of organic-inorganic composite materials in building reinforcement. Inspired by traditional glutinous rice mortar, a modified MICP technology has been developed, which integrates glutinous rice slurry into the MICP process.

In this study, rice straw and cattle manure powder were selected as additive materials to modify the rammed earth from the foundation of a local construction site, thereby preparing green rammed earth. Subsequently, the modified MICP technology was adopted for the solidification treatment of the green rammed earth, and compressive strength tests and flexural strength tests were conducted to evaluate its mechanical properties.

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2 Materials and Methods

2.1 Experimental Materials

This study focuses on green rammed earth, which is prepared by mixing rice straw, cattle manure powder, and raw rammed earth. After subjecting the green rammed earth to reinforcement treatment via the Microbially Induced Calcite Precipitation (MICP) technology, the relationship between flexural strength and compressive strength of the green rammed earth under different mass fractions of straw content was tested. The rice straw was sourced from a crop processing plant in Yueyang, Hunan Province, and mostly exists in the form of small fragments. It possesses moderate hardness, enabling it to intertwine well with soil particles and exhibit strong synergistic deformation capacity. Meanwhile, the rice straw has an appropriate thickness, distributes relatively uniformly in the soil matrix, and demonstrates high reliability in mechanical properties. The cattle manure powder was purchased from Yunwu Agricultural Supplies Online Store in Linyi, Shandong Province. The cattle manure fibers are relatively thick and structurally stable, which can effectively promote the formation of soil macroaggregates in the mixed soil and significantly enhance the strength and stability of the soil. The raw rammed earth was collected from the foundation construction site of a local construction project in Changsha, and its particle size distribution curve is presented in Figure 1.

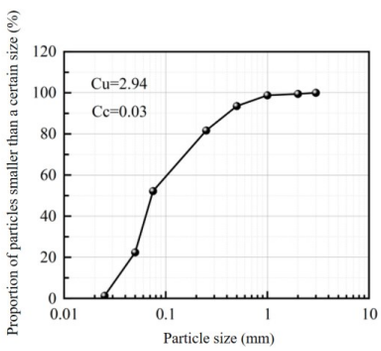


Figure 1 Particle gradation of rammed earth in its original state

During the Microbially Induced Calcite Precipitation (MICP) process, *Sporosarcina pasteurii* was adopted as the urease-producing microorganism; glutinous rice flour was purchased from a commercial supermarket. The preparation method of glutinous rice slurry was as follows: glutinous rice flour was placed in an electric rice cooker, and water was mixed with glutinous rice flour at an appropriate ratio so as to obtain glutinous rice slurry. Subsequently, the glutinous rice slurry was replaced by a mixture of *Sporosarcina pasteurii* bacterial solution cultured in 3% rice slurry and 1 mol/L cementing solution prepared with 3% rice slurry, at a volume ratio of 1:1.The rice straw was treated by soaking in a 2% NaOH solution for 24 hours. This treatment process can remove lignin, degrade hemicellulose, and modify the crystalline structure of cellulose, thereby enhancing the accessibility and utilization efficiency of cellulose. Finally, the rice straw was rinsed thoroughly and dried in an oven at 80℃ for 48 hours to obtain the straw samples required for the experiment. By incorporating the aforementioned materials, traditional rammed earth can be modified into a high-performance green rammed earth.

2.2 Experimental Methods

The preparation of green rammed earth adopted a one-time loading method, and the test specimens were fabricated at the water-impenetrable boundary of the materials required for green rammed earth. The dimensions of the specimens were 160 mm × 40 mm × 40 mm. Prior to specimen preparation, the treated straw, cattle manure powder, and loess powder were all oven-dried. The required mass of straw, cattle manure powder, and loess powder for each group of specimens was calculated based on the maximum dry density of the specimens, and the prepared materials were homogeneously mixed with water. Subsequently, the inner surface of the test mold was coated with petroleum jelly, the mixed materials were evenly placed into the mold and covered with the mold lid, and the assembled test mold was placed under a universal testing machine for pressure holding treatment to achieve the effective compaction density. Finally, after the completion of the pressure holding time, the specimens were demolded, arranged neatly, and subjected to air-drying treatment.

For the culture of Sporosarcina pasteurii, the strain was first activated at the start of the experiment, then inoculated into the basal medium, and subjected to expanded culture under preset environmental conditions. No additional nutrients were supplemented and no system disturbance was allowed during the process to ensure the continuity and stability of the culture, thereby providing a homogenized bacterial source for subsequent monitoring of growth characteristics, determination of functional activity, and experiments on the effects of environmental factors [5].

In this study, green rammed earth specimens with cattle manure contents of 5%, 10%, and 15%, as well as those with

straw contents of 5%, 10%, 15%, and 20%, were prepared. After air-drying, the specimens were placed on a Sans CMT5105 universal testing machine to conduct unconfined flexural and compressive strength tests. The unconfined compressive strength of different straw-cattle manure-earth specimens was measured to determine the optimal mix ratio of straw-cattle manure-earth.

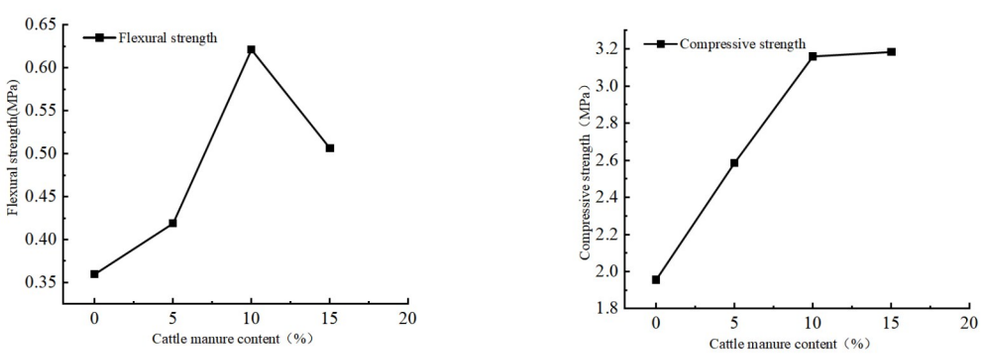
3 Results and Analysis

3.1 Effect of Cattle Manure Content on Soil Solidification Effect

Figure 2 illustrates the relationship between the variation of cattle manure content and the compressive strength as well as flexural strength of green rammed earth. As the cattle manure content increases from 0% to 15%, the flexural strength of green rammed earth exhibits a trend of first increasing and then decreasing, with the optimal content determined as 10%. For the compressive strength, it shows a continuous upward trend when the content rises from 0% to 10%, and tends to stabilize once the content reaches 10%—the subsequent increase in cattle manure content exerts a negligible effect on the compressive strength, maintaining a stable state.

The analysis of the influence of cattle manure content on the flexural strength of the material is as follows: when the cattle manure content is in the range of 0%–10%, the organic fibers contained in cattle manure may enhance the toughness of the internal structure of rammed earth and promote the formation of a denser flexural resistance network; when the cattle manure content is in the range of 10%–15%, excessive cattle manure will increase the porosity of the material, thereby impairing the overall continuity (induced by local fracture caused by fiber overload).

The analysis of the influence of cattle manure content on the compressive strength of the material is as follows: the cementitious substances in cattle manure may fill the gaps between rammed earth particles, thereby improving the compactness of the material; during the stable stage, the porosities have been fully filled, and the additional cattle manure is difficult to further enhance the material's compactness, resulting in stagnation in strength growth. The dosage of cattle manure exerts a significant regulatory effect on the strength of green rammed earth, with 10% identified as the critical dosage—excessive incorporation will lead to the performance degradation of green rammed earth.



(a) Flexural Strength Diagram

(b) Compressive Strength Diagram

Figure 2 Graph of the effect of cattle manure content on flexural strength and compressive strength

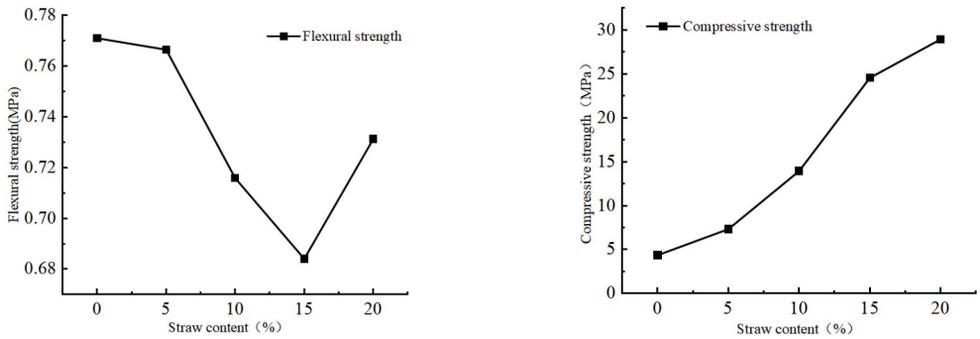
3.2 Effect of Straw Content on the Mechanical Properties of Solidified Soil

Figure 3 shows the effect of straw mass fractions on the flexural and compressive strengths of green rammed earth (cattle manure powder content fixed at 10%). As indicated, with increasing straw content, the flexural strength initially decreases slowly (0%–5%), accelerates sharply after 5%, reaches the minimum at 15%, and slightly recovers at 20%. The mechanism is that a small amount of straw has poor bonding with the soil matrix, weakening flexural performance; while higher content forms an effective reinforcing network, improving flexural strength. In contrast, compressive strength increases continuously with straw content. Within 0%–20%, cattle manure stably enhances the compressive performance of the solidified soil.

3.3 Effect of Straw Content on the Mechanical Properties of Solidified Soil After MICP Treatment

After MICP solidification of green rammed earth, the influence of straw content (different mass fractions) on its flexural and compressive strengths was investigated. As shown in Figure. 4, the flexural strength exhibits no obvious increase when straw content ranges from 0% to 5%, decreases sharply between 5% and 15%, and rebounds slightly from 15% to 20%. The underlying mechanisms are as follows:

At a straw content of 5%, low-dosage straw forms a sparse three-dimensional network structure, retarding crack propagation via the bridging effect; the bacterial solution generates a small amount of $CaCO_3$ particles on the fiber surface, thereby increasing the interface friction coefficient.

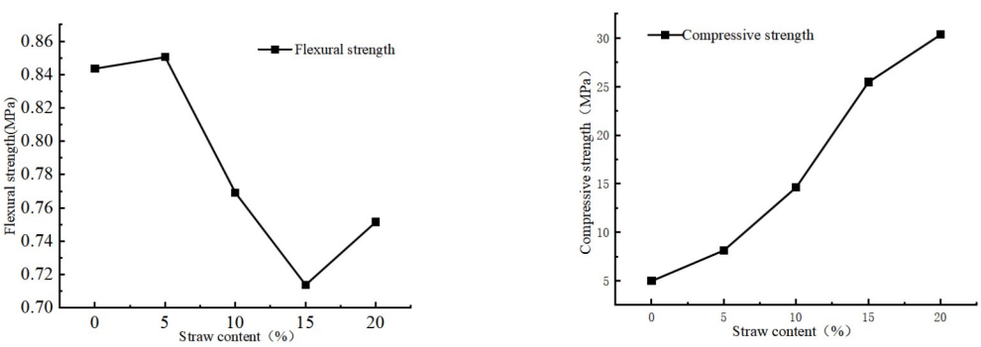


(a) Flexural Strength Diagram (b) Compressive Strength Diagram

Figure 3 Variation curves of effects of straw content on flexural and compressive strength of solidified soil

In the range of 5%–15% straw content, reduced fiber spacing is not accompanied by timely filling of interfaces with mineralized products; stress concentration occurs at fiber intersections, accelerating crack growth. Moreover, high straw content hinders the uniform diffusion of the bacterial solution, leading to insufficient local mineralization of the matrix and an increased proportion of brittle fracture.

When straw content exceeds 15% (15% – 20%), fiber spacing narrows to less than 0.5 mm, forming a continuous network that disperses loads through multi-level bridging and seals pore structures, promoting bacterial enrichment on fiber surfaces. During late curing and weathering, the coverage of $CaCO_3$ at interfaces increases, and fiber breakage replaces interface debonding as the dominant failure mode.Similarly, the compressive strength of MICP-solidified green rammed earth continuously increases with rising straw content.



(a) Flexural Strength Diagram (b) Compressive Strength Diagram

Figure 4 Variation curves of effects of straw content on flexural and compressive strength of solidified soil after MICP solidification

3.4 Analysis of Compressive Strength of Green Rammed Earth at 10% Strain

In the compressive strength tests of green rammed earth in this study, the test continued and the compressive strength showed a continuous increasing trend when the specimens were compressed to more than half their original height. Therefore, considering the requirement for a certain degree of damage resistance in practical applications, strict restrictions were imposed on the damage degree of straw-modified rammed earth. In the context of static mechanics, the commonly adopted limit value is 15%; while in dynamic scenarios, the limit value is 5%. These two limit values provide a key reference for investigating the effect of straw content on the performance of rammed earth [6-8].To fully understand the mechanical behavior of green rammed earth under different strain states, the strain value of 10% was selected based on relevant curve data to conduct an in-depth analysis of its mechanical response at this strain.

As shown in Figure 5, the compressive strength of solidified specimens was slightly higher than that of unsolidified ones for all straw contents, but the strength difference narrowed with increasing straw content. Solidification enhancement was most significant at low contents, while at high contents, the strengths were almost identical and the enhancement effect was nearly negligible. With highly synchronized trends of the two curves, straw content is the dominant factor affecting compressive strength. Solidification only slightly improves strength at low straw contents but cannot reverse the weakening effect of high straw content on soil compressive performance.

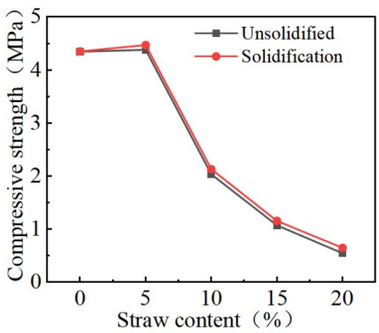


Figure 5 Comparison curves of compressive strength at 10% strain

4 Conclusions

This study focused on the mechanical properties of green rammed earth and the cultivation of Sporosarcina pasteurii in the MICP process. Addressing the limitations of traditional rammed earth construction materials and technologies, research was conducted on green rammed earth, with the main findings as follows:

(1) Flexural and compressive tests of green rammed earth show a mutually restrictive effect of cattle manure content: flexural strength peaks at 10%, while compressive strength stabilizes with a slight increase above 10%.

(2) With MICP technology, appropriate straw improves rammed earth ' s mechanical properties; excessive straw inhibits $CaCO_3$ precipitation, reducing strength.

(3) For unsolidified green rammed earth, flexural strength follows "slow decrease - sharp decrease - recovery" with increasing straw content, while compressive strength rises continuously. Low straw weakens the flexural structure, and high content forms a reinforcing network for slight recovery.

(4) After MICP solidification, flexural strength of green rammed earth shows "slow increase - sharp decrease - recovery" with straw content, and compressive strength remains on the rise. Solidification only slightly enhances strength at low straw contents, with the effect nearly negligible at high contents.

(5) At 10% strain, the compressive strength trends of solidified and unsolidified green rammed earth are highly synchronized, and straw content is the dominant factor affecting strength.

Funding

2023 Central Agricultural Machinery Research and Development, Manufacturing, Promotion, and Integrated Application Pilot Fund, China Project (Hunan Finance Department's Pre- [2023] No. 204 Document); the Natural Science Foundation project of Hunan Province, China (NO: 2024JJ5208)

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