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Mechanical Performance of Soft Soil Stabilized with Bamboo Chips: Evaluation of Compaction, CBR, and UCS Characteristics

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ABSTRACT
Soft soils are characterized by low bearing capacity and high compressibility, which pose challenges for road subgrades and embankment construction. This study evaluates the effectiveness of bamboo chips as an environmentally friendly stabilizing material for soft soils. Laboratory experiments were conducted using bamboo chip contents of 0%, 25%, 30%, and 35% by dry soil weight. The investigated parameters included compaction characteristics, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS). The results showed that increasing bamboo chip content reduced the maximum dry density while increasing the optimum moisture content. In addition, both CBR and UCS values improved significantly, with the optimum performance achieved at a bamboo chip content of 30%, resulting in a maximum CBR value of 13.33% and a UCS of 317.206 kPa. The improvement is attributed to enhanced particle interlocking and more uniform stress distribution within the soil matrix. These findings indicate that bamboo chips have strong potential as a sustainable alternative material for improving the engineering properties of soft soils in subgrade and embankment applications.

Keywords: *Bamboo chips; California Bearing Ratio (CBR); Soft Soil; Unconfined Compressive Strength (UCS); Soil Stabilization.*

1. Introduction

Subgrade conditions are a critical factor influencing the stability and performance of engineering structures. A common issue arises in soft soils, which are characterized by low bearing capacity and high compressibility, making them susceptible to excessive settlement and instability [1], [2]. Various soil stabilization methods have been applied, such as the use of cement and lime; however, these approaches are associated with relatively high costs and potential environmental impacts. Specifically, the use of cement and lime may induce extreme alkalinity that disrupts soil biological structures and causes the soil to become brittle, leading to shrinkage cracking over time [3], [4].

The implementation of sustainable development principles encourages the use of environmentally friendly and cost-effective alternative materials. Indonesia has abundant bamboo resources with significant potential for geotechnical applications [5]. Although previous studies have demonstrated the effectiveness of bamboo-based materials for soil stabilization, most research has focused on bamboo fibers or treated bamboo products. Limited studies have investigated the use of bamboo chips for soft soil stabilization, particularly regarding the evaluation of optimum content based on compaction characteristics, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS). In addition, the combined influence of bamboo chips on these engineering properties has not been comprehensively examined.

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The inclusion of bamboo chips can improve soil performance through reinforcement mechanisms such as particle interlocking, bridging, and stress redistribution, which enhance shear resistance, bearing capacity, and compressive strength [6], [7], [8], [9] Moreover, the water absorption capacity and low specific gravity of bamboo influence the compaction characteristics of the soil, particularly the optimum moisture content and maximum dry density [10].

Therefore, this study evaluates the effectiveness of bamboo chips as a sustainable physical stabilization material for soft soils by investigating the influence of varying bamboo chip contents on compaction characteristics, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS). Unlike previous studies focusing on bamboo fibers, bamboo strips, or bamboo biochar, this research investigates bamboo chips as randomly distributed discrete reinforcement to identify the optimum content for improving the engineering properties of soft soil. The study also aims to determine the optimum bamboo chip content that provides the most effective improvement in soil mechanical performance.

2. Materials and Methods

This study is an experimental investigation conducted in a laboratory to evaluate the effect of varying bamboo chip content on the mechanical performance of soft soil. The laboratory testing methods employed include compaction testing (Proctor), California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS). The test results were analyzed to identify the relationship between bamboo chip content and changes in soil mechanical performance.

2.1. Research Materials

The materials used in this study consist of soft soil and bamboo chips as a stabilizing agent. The soil samples were obtained from the retention basin area of Universitas Pembangunan Nasional Veteran Jawa Timur, as illustrated in Figure 1. The collected soil was oven-dried at 105 ± 5°C for 24 hours prior to testing. Laboratory testing results indicated that the soil has a liquid limit in oven-dried condition (LL_{oven}) of 64.14% and a liquid limit in air-dried condition ($LL_{air\text{-}dried}$, dried at room temperature for 4–5 days) of 92.09%, a plastic limit (PL) of 44.92%, and a plasticity index (PI) of 19.22%.

In addition, the ratio between the liquid limit of air-dried soil and oven-dried soil (LL_{oven}/ $LL_{air\text{-}dried}$) was obtained as 0.696, which is lower than 0.75. This condition indicates the presence of organic content in the soil, consistent with its classification as organic clay (OH). Based on these index properties, the soil is classified as organic clay of high plasticity (OH) according to both AASHTO and the Unified Soil Classification System (USCS) [11].

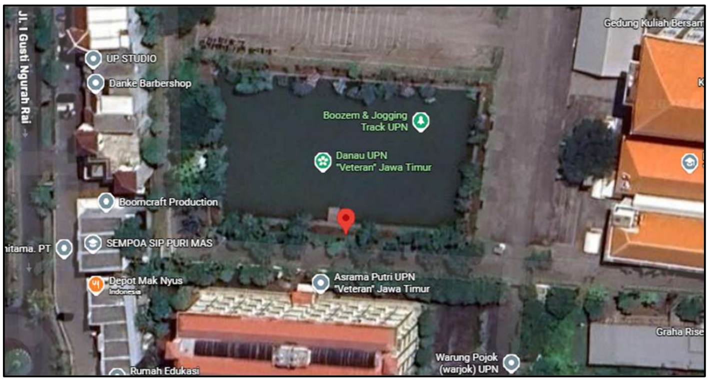

Figure 1. Soil Sampling Location (Google Maps, 2026)

The bamboo chips used in this study were derived from Javanese bamboo (*Gigantochloa atroviolacea*), as shown in Figure 2. The average moisture content of the bamboo chips was 14,67%.

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Figure 2. Javanese Bamboo (Researcher Documentation,2026)

The selection of Javanese bamboo was based on its relatively superior mechanical properties compared to other bamboo species, such as apus bamboo and petung bamboo, particularly in terms of Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) [6]. These parameters indicate the ability of the material to resist deformation and applied loads, making Javanese bamboo a suitable reinforcement material for soil stabilization applications. As presented in Table 1, Javanese bamboo exhibits higher MOE and MOR values than the other bamboo species, indicating greater stiffness and bending strength. These characteristics support its selection as the reinforcing material in this study.

Table 1. Mechanical and Physical Properties of Apus, Wulung, and Javanese Bamboo

Apus Bamboo					Wulung / Jawa Bamboo					Petung Bamboo				
Length	Static Modulus of Elasticity (MOE)	Modulus of Rupture (MOR)	Moisture Content	Density	**Length**	Static Modulus of Elasticity (MOE))	Modulus of Rupture (MOR)	Moisture Content	Density	**Length**	Static Modulus of Elasticity (MOE)	Modulus of Rupture (MOR)	Moisture Content	Density
m	MPa	Mpa	%	Kg/m3	m	MPa	Mpa	%	Kg/m3	m	MPa	Mpa	%	Kg/m3
2.710	13106	74	13	636	**3.342**	21919	92	14	584	**3.839**	779	49	17	673
3.272	17033	85	13	699	**3.256**	22563	94	14	636	**4.176**	12963	71	15	750
3.198	17438	86	13	532	**3.365**	20443	92	13	667	**3.783**	18023	67	14	708
3.388	20354	94	13	694	**3.350**	15416	80	12	563	**3.561**	17986	70	14	724
3.335	19106	89	13	645	**3.287**	11969	66	14	597	**4.154**	14695	52	14	643
3.580	14992	80	13	605	**2.851**	14775	83	13	619	**3.833**	13527	37	16	704
3.190	19100	94	13	626	**3.172**	20746	91	14	694	**3.827**	16727	71	15	676
2.925	18402	88	13	660	**3.445**	21779	92	13	664	**3.786**	10047	44	14	767
3.790	17863	80	14	643	**3.163**	15818	62	14	546	**3.786**	11323	44	15	668
2.842	19177	94	12	732	**3.312**	21830	96	14	643	**3.581**	18562	72	14	684
2.799	15421	75	13	553	**3.389**	19018	89	13	702	**4.061**	15446	93	14	741
3.926	16690	76	14	569	**3.433**	18031	80	14	611	**3.631**	22317	108	14	759
	17390	85	13	633		18692	85	13	627		14366	65	15	708
	13106	74	12	532		11969	62	12	546		779	37	14	643
	20354	94	14	732		22563	96	14	702		22317	108	17	767

2.2. Mixture Variation and Bamboo Chip Gradation

The samples in this study consisted of natural soil (0% bamboo chips) and soil mixtures containing 25%, 30%, and 35% bamboo chips by dry soil weight. These bamboo chip contents were selected as a preliminary range based on preliminary observations and previous studies reporting that bamboo-based reinforcement at moderate to relatively high contents can significantly improve soil mechanical properties while maintaining adequate soil continuity and workability [7]. The selected range was intended to capture the variation in engineering behavior from moderate to high reinforcement levels and to identify the optimum bamboo chip content in terms of compaction characteristics, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS). Contents below 25% were considered insufficient to produce a noticeable reinforcing effect. In contrast, contents exceeding 35% were expected to increase the void ratio and reduce effective soil–particle contact, thereby adversely affecting soil performance.

In addition to bamboo chip content, the reinforcement material was classified into three size groups: small (5–10 mm), medium (10–20 mm), and large (20–25 mm). A gradation consisting of

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40% small, 40% medium, and 20% large particles was adopted to improve particle packing and enhance the interaction between soil and bamboo chips through filling and interlocking mechanisms. Bamboo chips were manually cut using a mechanical cutter and subsequently sieved into the designated size fractions. The size distribution of the bamboo chips used in this study is presented in Figure 3.

(a) (b) (c)

Figure 3. Bamboo Chips: (a) 5-10 mm, (b) 10-20 mm, and (c) 20-25 mm (Research Documentation, 2026)

2.3. Sample Preparation and Mixing Procedure

The Unconfined Compressive Strength (UCS) test was initially conducted on undisturbed soil samples to determine the baseline strength of the natural soil. Subsequently, Standard Proctor compaction tests were performed in accordance with SNI 1742:2008 to determine the optimum moisture content (OMC) and maximum dry density (MDD) of the natural soil and each bamboo chip mixture variation. The UCS tests were conducted in accordance with ASTM D2166, while the California Bearing Ratio (CBR) tests were carried out following SNI 1744:2014.

The soil and bamboo chips were manually dry-mixed according to the predetermined proportions for approximately 5 minutes until a uniform distribution was achieved. Water was then sprayed gradually while the mixture was continuously stirred to ensure homogeneous moisture distribution based on the corresponding OMC value of each mixture. The prepared mixtures were used to produce CBR and UCS specimens.

For each mixture variation and each testing type, three identical specimens were prepared and tested to ensure result reliability. After preparation, all specimens were sealed in plastic bags and allowed to equilibrate for 24 hours prior to testing at room temperature (±27°C).

3. Results and Discussions

3.1. Compaction Test (Proctor)

Based on Figure 4, the compaction test results of the natural soil indicate a relationship between moisture content and dry density (γd), where γd increases with increasing moisture content until reaching the optimum moisture content (OMC), and subsequently decreases beyond this point [10]. The interaction between soil particles and water during compaction is the primary factor influencing changes in dry density. At low moisture content, interparticle friction remains dominant, limiting particle movement and hindering densification. The addition of water enhances lubrication between particles, allowing them to rearrange into a denser configuration and resulting in higher γd values. However, beyond the optimum moisture content, excess water occupies the voids between particles and reduces the effectiveness of compaction energy, leading to a decrease in dry density [8].

Changes in compaction characteristics due to the addition of bamboo chips are illustrated in Figures 5 and 6. The inclusion of this material results in a significant reduction in the maximum dry density (γd max) compared to the natural soil that has been conditioned at its optimum moisture content (OMC). In contrast, the optimum moisture content (OMC) increases across all mixture variations. The decrease in γd max is attributed to the lower specific gravity of bamboo chips and the increase in void volume within the mixture, which reduces the maximum achievable density [9].

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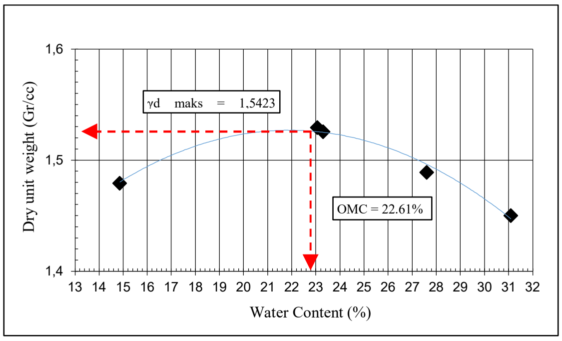

Figure 4. Relationship between Moisture Content and Dry Density (γd) (*Laboratory Test Results, 2026)*

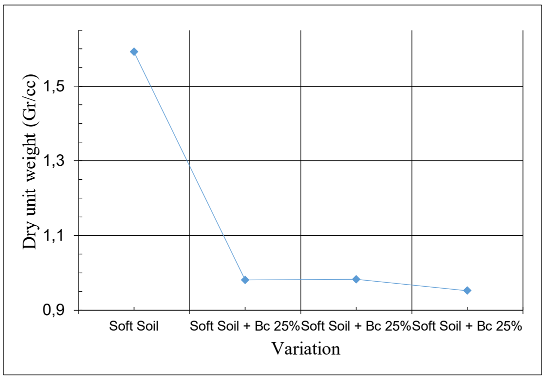

Figure 5. Effect of Mixture Variation on Dry Density (γd) (Laboratory Test Results, 2026)

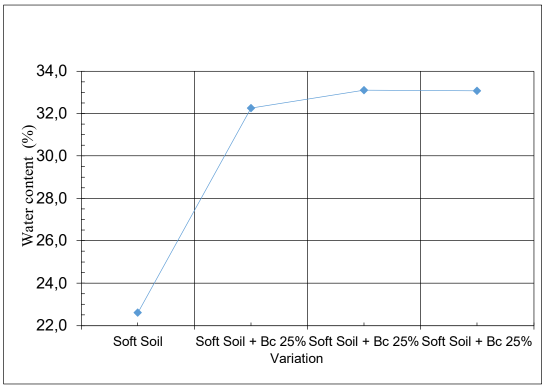

Figure 6. Effect of Mixture Variation on Optimum Moisture Content (OMC) (*Laboratory Test Results, 2026)*

Table. 2. Compaction Test Results (Laboratory Test Results, 2026)

Compaction Test (Proctor)				
	Soft Soil	Soil + Bamboo Chips 25%	Soil + Bamboo Chips 30%	Soil + Bamboo Chips 35%
Dry Density (γd)	1,54	1,004	0,930	0,932
Optimum Moisture Content (OMC)	22,61	32,26	33,11	33,07

As shown in Table 2, the incorporation of bamboo chips significantly influenced both the maximum dry density (γd) and the optimum moisture content (OMC) of the soil. The maximum dry density decreased from 1.54 g/cm³ for untreated soft soil to 1.004 g/cm³, 0.930 g/cm³, and 0.932 g/cm³ for mixtures containing 25%, 30%, and 35% bamboo chips, respectively. This reduction is attributed to the lower specific gravity and irregular geometry of bamboo chips, which increase the void ratio and reduce particle packing efficiency during compaction. Conversely, the OMC increased because the hygroscopic nature and water absorption capacity of bamboo chips reduced the amount of free water available for soil lubrication, requiring additional water to overcome internal friction and achieve maximum dry density [12].

3.2. Unsoaked CBR Test

The results of the California Bearing Ratio (CBR) test for natural soil and bamboo chip mixture variations are presented in Table 3, as well as in Figures 7 and 8. The CBR test is used to evaluate the subgrade bearing capacity based on the soil's resistance to penetration at standard penetration levels.

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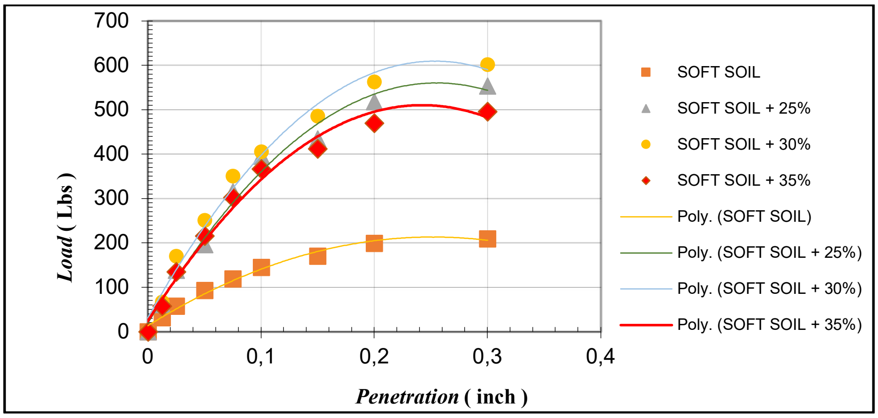

Figure 7. Load and Penetration Relationship in the CBR Test (Laboratory Test Results, 2026)

Table 3. Summary California Bearing Ratio (CBR) Test Results (Laboratory Test Results, 2026)

	CBR Test			
Variation	**Soft Soil**	**Soil + Bamboo Chips 25%**	**Soil + Bamboo Chips 30%**	**Soil + Bamboo Chips 35%**
CBR (10 blows)	2,77	8,00	10,00	7,83
CBR (30 blows)	4,00	10,50	12,00	9,33
CBR (65 blows)	4,83	12,00	13,33	11,50
Maximum	4,83	12,00	13,33	11,50

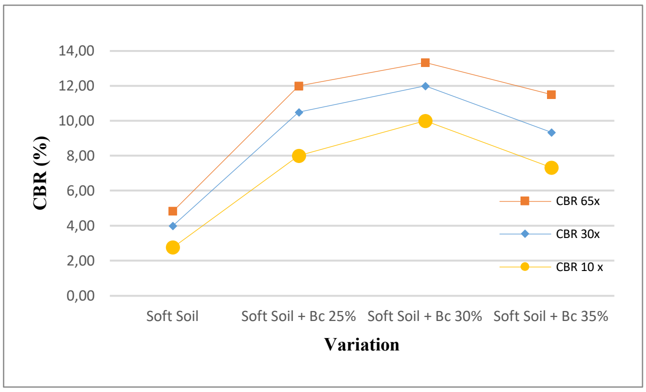

Figure 8. Relationship between Bamboo Chip Content and CBR Value (*Laboratory Test Results, 2026)*

Figures 7 and 8 present the load–penetration behavior and the relationship between bamboo chip content and CBR values under different compaction efforts. Figure 7 shows that the untreated soil exhibits the lowest load resistance throughout the penetration process, whereas the incorporation of bamboo chips produces steeper load–penetration curves with higher peak loads, indicating improved stiffness and bearing capacity. Figure 8 further confirms this trend, showing that CBR values increase with bamboo chip addition up to 30% and decrease slightly at 35%, although they remain substantially higher than those of the untreated soil. In addition, increasing the compaction effort from 10 to 65 blows resulted in progressively higher CBR values for all mixtures, indicating that greater compaction enhances soil density and penetration resistance.

Table 3 summarizes the CBR values of untreated soil and bamboo chip-reinforced soil under three compaction efforts. The untreated soil exhibited CBR values of 2.77%, 4.00%, and 4.83% at 10, 30, and 65 blows, respectively. The incorporation of 25% bamboo chips increased the CBR values to 8.00%, 10.50%, and 12.00%, while the 30% bamboo chip mixture produced the highest values of 10.00%, 12.00%, and 13.33%. Increasing the bamboo chip content to 35% reduced the CBR values to 7.83%, 9.33%, and 11.50%, although these values remained significantly higher than

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those of the untreated soil. These results indicate that 30% bamboo chip content provides the optimum improvement in bearing capacity under the tested conditions.

The improved bearing capacity at bamboo chip contents of 25%–30% can be attributed to the formation of a reinforcing network within the soil matrix. Acting as discrete inclusions, bamboo chips enhance interparticle interlocking and facilitate load transfer through bridging mechanisms, thereby improving stress distribution and increasing penetration resistance, resulting in higher CBR values [13]. However, beyond the optimum bamboo chip content (30%), the reinforcing efficiency declined. At 35% bamboo chip content, the excessive amount of bamboo chips increased the void ratio and reduced effective interparticle contact within the soil matrix. These conditions decreased the continuity and density of the soil skeleton, resulting in less efficient stress transfer under penetration loading and consequently lower bearing capacity [9].

3.3. Unconfined Compressive Strength (UCS) Test

The results of the Unconfined Compressive Strength (UCS) test for natural soil and bamboo chip mixture variations are presented in Figures 9. The UCS value is used to evaluate the ability of soil to withstand axial loading without lateral confinement.

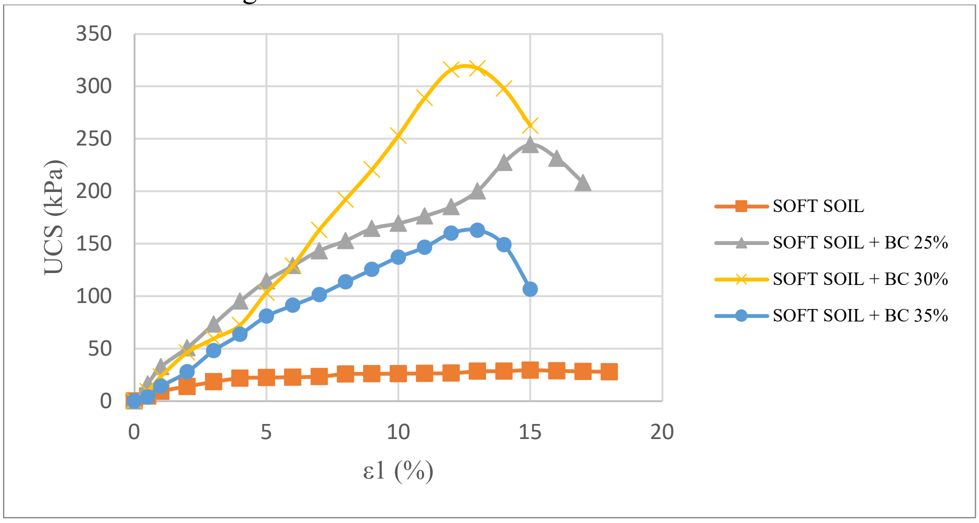

Figure 9. Stress and Strain Relationship in UCS Testing (*Laboratory Test Results, 2026)*

Figure 9 illustrates the stress–strain behavior of untreated soft soil and soil reinforced with different bamboo chip contents under UCS loading. The untreated soil exhibits a relatively low stress response accompanied by large axial deformation, reflecting its soft and weak structural characteristics. The absence of a distinct peak stress indicates predominantly ductile failure behavior. In contrast, the incorporation of bamboo chips significantly enhances the stress response, resulting in steeper stress–strain curves, higher peak stresses, and increased stiffness. The reinforced specimens exhibit a gradual transition from ductile to more brittle failure, as evidenced by the appearance of a distinct peak stress followed by post-peak softening. Among the reinforced specimens, the 30% bamboo chip mixture exhibited the highest peak stress, while the 35% mixture showed a reduction in peak stress compared with the 25% and 30% mixtures, although it remained significantly stronger than the untreated soil.

The unconfined compressive strength (UCS) increased markedly with the incorporation of bamboo chips, rising from 29.528 kPa for the untreated soil to 244.470 kPa and 317.206 kPa at bamboo chip contents of 25% and 30%, respectively. These values correspond to strength improvements of approximately 727.8% and 974.1% relative to the untreated soil. Although the UCS decreased to 162.770 kPa at a bamboo chip content of 35%, this value still represents a 451.1% increase compared with the untreated soil. The highest UCS was therefore achieved at 30% bamboo chip content, indicating that this proportion provides the optimum reinforcing effect under the tested conditions.

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The improvement in compressive strength at bamboo chip contents of 25% and 30% can be attributed to the reinforcing mechanism provided by the bamboo chips. Acting as discrete reinforcement elements, bamboo chips generate a bridging effect that enhances interparticle interlocking and increases the apparent cohesion of the soil. These mechanisms restrict particle displacement under axial loading, thereby improving deformation resistance, soil stability, and bearing capacity [14]. However, increasing the bamboo chip content to 35% reduced the reinforcing efficiency. The decrease in UCS indicates that excessive bamboo chips increase the void ratio while reducing effective interparticle contact within the soil matrix. As a result, stress transfer between soil particles becomes less efficient, leading to a reduction in compressive strength [15]. This observation is consistent with previous studies reporting that bamboo reinforcement improves soil strength only up to an optimum dosage, beyond which excessive reinforcement reduces the overall density of the mixture [16]. Furthermore, the lower specific gravity of bamboo compared with soil particles decreases the bulk density of the composite material, limiting the contribution of the soil matrix to strength development [17]. The irregular geometry of bamboo chips also promotes the formation of larger voids, creating localized stress concentrations that accelerate failure under compressive loading [18].

4. Conclusions

The addition of bamboo chips significantly influences the mechanical performance of soft soil. The test results indicate that the maximum dry density (γd max) decreases with increasing bamboo chip content, while the optimum moisture content (OMC) increases.

The results of the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) tests show a substantial improvement compared to the original soil. At an optimum bamboo chip content of 30%, the CBR value increased by 176%, while the UCS value increased by 974.1% relative to the initial condition.

The improvement in CBR and UCS values is associated with the formation of internal reinforcement mechanisms, namely interlocking and bridging effects, which enhance the soil's resistance to loading. However, excessive addition of bamboo chips leads to a decline in mechanical performance due to reduced effective interaction between soil particles and an increase in void volume within the mixture. Based on these results, the optimum bamboo chip content for improving the mechanical performance of soft soil is approximately 30%.

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