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HYBRID NATURAL GEOTEXTILES FOR SUSTAINABLE GROUND IMPROVEMENT: INSIGHTS FROM UCC, CBR, AND DIC ANALYSES

NARAVNI HIBRIDNI GEOTEKSTILI ZA TRAJNOSTNO IZBOLJŠANJE NOSILNOSTI TAL; VPOGLED NA OSNOVI UPORABE ANALIZE S TEHNIKO NEOMEJENE KOMPRESIJE, KALIFORNIJSKEGA RAZMERJA NOSILNOSTI IN DIGITALNE KORELACIJE SLIK

Saranya Nithiyanandan[1*], Ganesh Kumar Shanmugam[2], Sivapriya Vijayasimhan[3]

[1]Department of Civil Engineering, Coimbatore Institute of Technology, Coimbatore 641014, Tamil Nadu, India
[2]Principal Scientist Geotechnical Engineering Division, CSIR–CBRI, Roorkee, Uttarakhand, India
[3]Department of Civil Engineering, Sri Sivasubramaniya Nadar College of Engineering, Chennai 603110, Tamil Nadu, India

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The growing need for environmentally sustainable ground improvement has accelerated the use of natural fiber geotextiles as alternatives to synthetic reinforcements. This study investigates the mechanical and deformation characteristics of clayey soil reinforced with coir and jute geotextiles, used individually and in hybrid configurations. Reinforcement layers were positioned at mid-height (H/2), one-third height (H/3), and as dual hybrid systems. Improved soil specimens compacted at dry-of-optimum (DOP), optimum-moisture-content (OMC), and wet-of-optimum (WOP) conditions were evaluated using Unconfined Compression (UCC), California Bearing Ratio (CBR), and Digital Image Correlation (DIC) techniques. Results indicate that specimens prepared at OMC consistently achieved the highest strength. Hybrid reinforcement with jute at the bottom and coir at the top (J-B, C-T) delivered the best overall performance, producing up to 45–55 % improvement in the UCC strength and more than two-fold enhancement in CBR compared with unreinforced soil under soaked conditions. DIC analysis confirmed a substantial reduction in strain localization and bulging in reinforced samples, with the lowest vertical strain (≈1.27 %) recorded for the hybrid system against 2.24 % for unreinforced soil. The findings demonstrate that hybrid coir–jute geotextile systems placed near the critical shear zone provide an effective, economical, and sustainable solution for improving the performance of pavement subgrades.

Keywords: coir–jute reinforcement, sustainable subgrade, UCC–CBR behavior, ground improvement

Naraščajoča potreba po okolju prijaznih in trajnostnih izboljšavah nosilnosti tal je pospešila razvoj in uporabo geotekstila iz naravnih vlaken kot alternative za sintetične ojačitve (armature). V tem članku avtorji predstavljajo študijo in raziskavo mehanskih ter deformacijskih lastnosti glinastih tal, ojačanih z geotekstilom iz kokosovih vlaken in jute, uporabljenih posamično in v različnih hibridnih konfiguracijah. Ojačitvene plasti so bile nameščene na srednji višini (H/2), tretjini višine (H/3) in kot dvojni hibridni sistemi. Izboljšani vzorci tal, zbiti pri suhem optimalnem stanju (DOP; angl.: dry-of-optimum), optimalni vlažnosti (OMC; angl.: optimal moisture content) in mokrem optimalnem stanju (WOP;; angl.: wet-of-optimum), so bili ocenjeni z uporabo tehnik neomejene kompresije (UCC; angl.: unconfined compression), kalifornijskega razmerja nosilnosti (CBR; angl.: California Bearing Ratio) in digitalne korelacije slik (DIC; angl.: Digital Image Correlation). Rezultati pričujoče raziskave kažejo, da so vzorci, pripravljeni pri OMC, dosledno dosegli najvišjo trdnost. Hibridna ojačitev z juto na dnu in kokosovimi vlakni na vrhu (J-B, C-T) je pokazala najboljšo splošno učinkovitost, saj je dosegla od 45 do 55 % izboljšanje trdnosti UCC in več kot dvakratno povečanje CBR v primerjavi z nearmiranimi tlemi v premočenih pogojih. Analiza DIC je potrdila znatno zmanjšanje lokalizacije deformacij in izboklin v ojačanih vzorcih, pri čemer je bila najnižja navpična deformacija (približno 1,27 %) zabeležena pri hibridnem sistemu v primerjavi z 2,24 % pri nearmirani zemlji. Ugotovitve kažejo, da hibridni geotekstilni sistemi iz kokosovih vlaken in jute, nameščeni v bližini kritičnega strižnega območja, zagotavljajo učinkovito, ekonomično in trajnostno rešitev za izboljšanje delovanja podlage vozišča.

Ključne besede: armatura iz kokosovih vlaken in jute, trajnostna podlaga, obnašanje UCC-CBR, izboljšanje nosilnosti tal

1 INTRODUCTION

Sustainable ground improvement has gained increasing attention due to the need to strengthen weak soils while reducing environmental impacts in infrastructure development. Synthetic geotextiles such as polypropylene and polyester are widely used for reinforcement because of their high tensile strength and durability; however, their non-biodegradable nature and contribution to microplastic pollution raise long-term sustainability concerns.[1,2] These limitations have encouraged the use of natural fiber geotextiles – particularly coir and jute – which are biodegradable, renewable, locally available, and have a lower environmental footprint.[3,4]

Coir geotextiles, produced from coconut husk, contain a high lignin content, resulting in superior resistance to biological degradation and good performance under wetting–drying cycles.[5,6] Their coarse surface enhances

*Corresponding author's e-mail:
saranyan@cit.edu.in (Saranya Nithiyanandan)

soil–geotextile interface friction and contributes to improved shear strength and settlement reduction.[7,8] Field studies further indicate their effectiveness in reducing rutting and extending pavement life in unpaved and rural roads.[9] Furthermore, studies have shown that coir geotextiles remain effective even under cyclic wetting–drying conditions, highlighting their resilience in tropical and high-rainfall regions.[10]

Jute geotextiles, known for their higher tensile strength and stiffness, improve load distribution and confinement in reinforced soils. Their benefits in road construction include increased bearing capacity and reduced rutting.[11] Modified jute products, such as latex-coated or polymer-treated fabrics, exhibit enhanced durability and have demonstrated CBR improvements under soaked conditions.[12,13] Owing to their affordability and availability in South Asia, jute materials support sustainable infrastructure in resource-constrained regions.[14]

The reinforcement mechanism of both fibers is governed by resistance to lateral deformation and interfacial shear mobilization, which collectively restrict soil deformation. The placement depth of reinforcement plays a major role, with layers closer to the shear bulb mobilizing higher confinement.[15,16] Recent studies also highlight the potential of hybrid systems and combinations with recycled or stabilized materials to enhance mechanical performance while supporting circular economy objectives.[17,18]

Although numerous studies have investigated coir or jute geotextiles as individual reinforcement layers, most have focused on isolated strength parameters without jointly examining deformation behavior and moisture-dependent performance. Comprehensive evaluations that integrate mechanical strength, strain localization characteristics, and soaked–unsoaked responses within a single experimental framework are still limited.

To address this research gap, the present study systematically investigates both single-layer and dual-layer hybrid coir–jute geotextile configurations placed at H/2 and H/3 depths. Unlike earlier works that relied primarily on conventional strength tests, this research combines Unconfined Compression (UCC), California Bearing Ratio (CBR) under soaked and unsoaked conditions, and Digital Image Correlation (DIC) techniques to capture not only peak strength but also deformation patterns and strain distribution. The inclusion of DIC enables direct visualization of bulging suppression and confinement mechanisms, offering quantitative insight into reinforcement efficiency. Furthermore, the study evaluates moisture sensitivity across different compaction states (dry of optimum, optimum, and wet of optimum), providing a realistic assessment of subgrade behavior under field-relevant conditions. The comparative assessment of reinforcement depth and hybrid fiber arrangement highlights the synergistic interaction between coir and jute, establishing an optimized configuration for enhanced load-bearing capacity and deformation control. Through this integrated and multi-parameter approach, the study advances current understanding of natural geotextile applications and strengthens their relevance for sustainable pavement subgrade improvement.

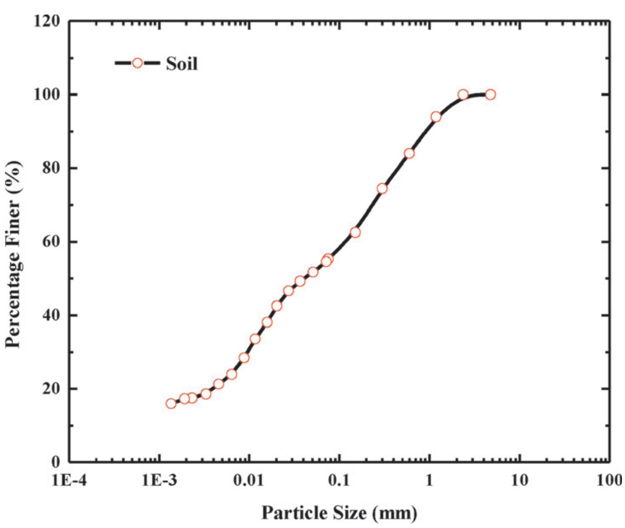

Figure 1: Grain size distribution of the investigated soil

2 MATERIALS & METHODOLOGY

The experimental program used locally available clayey soil, classified as CH under the Unified Soil Classification System. The soil was oven dried, pulverized, and sieved through a 4.75 mm IS sieve. Basic geotechnical properties, including specific gravity, Atterberg limits, and grain size distribution (**Figure 1**), were determined as per ASTM standards. Based on the compaction curve, specimens were prepared under three moisture conditions: the optimum moisture content (OMC), corresponding to a maximum dry density of 22.75 kN/m^3 at 16 % water content; the dry-of-optimum condition (DOP), with a dry density of 22.5 kN/m^3 at 13.5 % water content; and at the wet-of-optimum condition (WOP), with a dry density of 22.5 kN/m^3 at 19 % water content. The results are summarized in **Table 1**.

Table 1: Geotechnical properties of the soil used in this study

Property	Value	Ref. No.
Specific gravity (G)	2.74	19
Liquid limit (LL, %)	52	20
Plastic limit (PL, %)	22	
Plasticity index (PI, %)	30	
Shrinkage limit (SL, %)	5.8	21
Percentage of fines	55.3 %	
Soil classification	CH	22
Max. dry density (kN/m^3)	22.75	23
Optimum moisture content (OMC, %)	16	

Reinforcement materials including woven coir geotextile (≈750 g/m^2) from Pollachi and jute geotextile (724 g/m^2) from Birlapur, India, were considered for this

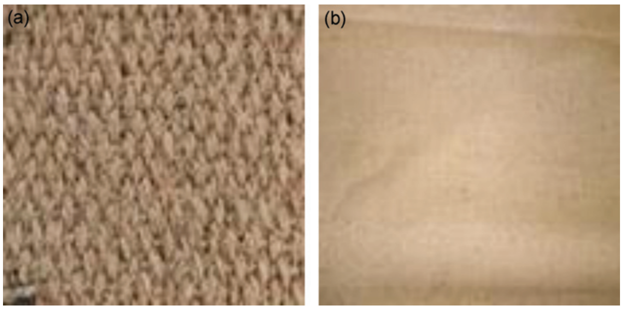

Figure 2: Photographic view of: a) coir and b) jute geotextiles

study and they are shown in **Figure 2**. Coir provided durability under wet conditions due to its high lignin content, while jute offered higher tensile stiffness. The physical and mechanical properties of these geotextile materials were evaluated in accordance with relevant ASTM standards. The mass per unit area was determined as per reference,[24] the tensile strength was based on reference,[25] and the elongation at break followed reference.[26] Jute exhibited a mass per unit area of 724 g/m^2, with a tensile strength of 10.22 MPa and an elongation of 16.07 %. In comparison, coir exhibited a higher mass per unit area of 800 g/m^2 and a superior tensile strength of 14.13 MPa, along with an elongation of 18.72 %.

Cylindrical specimens (38 × 76) mm were compacted with geotextile layers inserted at selected depths.

Four reinforcement configurations were considered in this study: a single layer placed at mid-height (H/2), a single layer positioned at one-third height (H/3), and two dual-layer hybrid configurations. In the hybrid arrangements, two different natural geotextiles (coir and jute) were inserted within the same specimen at two distinct vertical locations, either with jute at the top and coir at the bottom (J-T, C-B) or with jute at the bottom and coir at the top (J-B, C-T). Unreinforced control specimens were also prepared for comparison. The adopted configurations are illustrated in **Figure 3**, and the corresponding notations are summarized in **Table 2**.

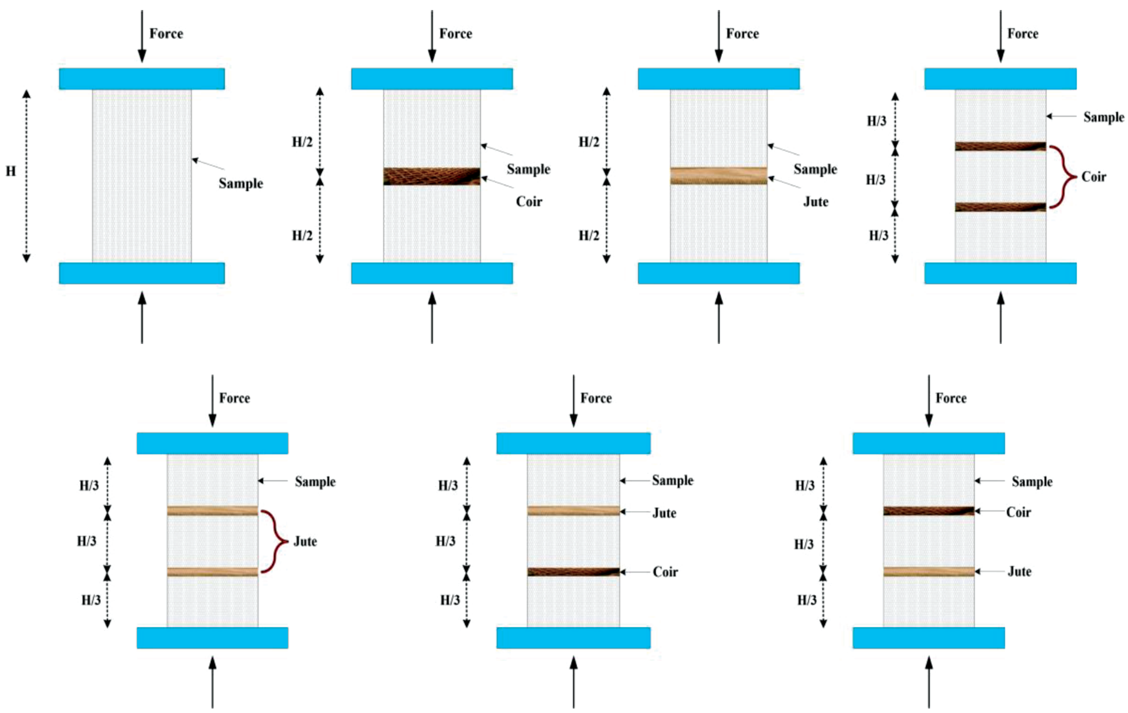

Figure 3: Schematic representation of the test configuration

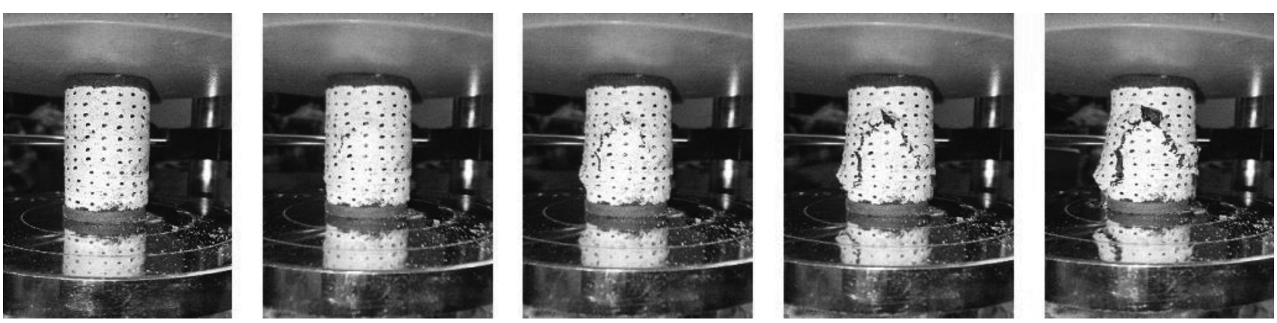

Figure 4: Visual sequence illustrating bulging and failure characteristics of soil specimens in UCC tests

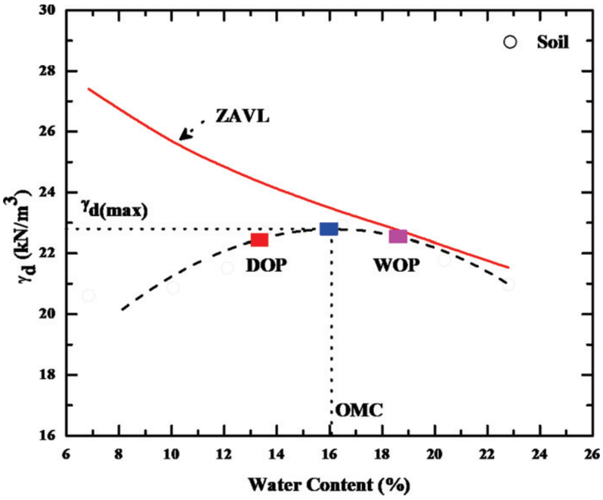

Figure 5: Compaction characteristics of the selected soil

Table 2: Reinforcement configurations

Reinforcement location	Notation
Coir placed at mid-height (H/2)	C-H/2
Jute placed at mid-height (H/2)	J-H/2
Coir placed at one-third height (H/3)	C-H/3
Jute placed at one-third height (H/3)	J-H/3
Jute at top and coir at bottom	J-T, C-B
Jute at bottom and coir at top	J-B, C-T

Unconfined Compression (UCC) tests were conducted in accordance with reference,[27] during which specimens were axially loaded at a constant strain rate until failure. The stress–strain response, peak strength, and corresponding deformation were recorded. To investigate the reinforcement mechanisms, selected specimens were monitored using the digital image correlation (DIC) technique, which enabled the measurement of surface deformation and the visualization of bulging patterns. Sequential images captured during UCC loading further illustrated the typical failure modes of both reinforced and unreinforced specimens, as presented in **Figure 4**. In addition, the California Bearing Ratio (CBR) value of the soil prepared at its optimum moisture content (OMC) was also determined.

3 RESULTS AND DISCUSSIONS

3.1 Compaction characteristics

The compaction characteristics of the selected soil were determined using the standard procedure, and the corresponding compaction curve is presented in **Figure 5**. Based on the curve, three compaction states were identified for conducting the UCC tests: one on the dry side of optimum, a corresponding point on the wet side of optimum, and the optimum moisture content (OMC). Specimens were prepared at these selected states and subsequently employed for both UCC and DIC analyses. Additionally, the soil compacted at OMC was utilized for the CBR test. The results and observations obtained from these tests are discussed in the following sections.

3.2 Unconfined compression response of soil at various configurations

The UCC test results clearly demonstrated that the soil compacted at the optimum moisture content (OMC) consistently achieved the highest shear strength compared to specimens compacted at the dry side of optimum (DOP) and wet side of optimum (WOP) as shown in **Figure 6**. This outcome is consistent with the principle that OMC offers the best balance of soil suction, pore water distribution, and particle rearrangement, resulting in maximum inter-particle contact and effective stress transfer. Similar findings were reported by reference,[4] highlighting that compaction at OMC enhances particle interlocking and shear resistance.

Among the reinforcement layouts, the dual-layer systems outperformed the single-layer placements, with the jute-bottom, coir-top (J-B, C-T) configuration delivering the maximum shear stress under all compaction states.

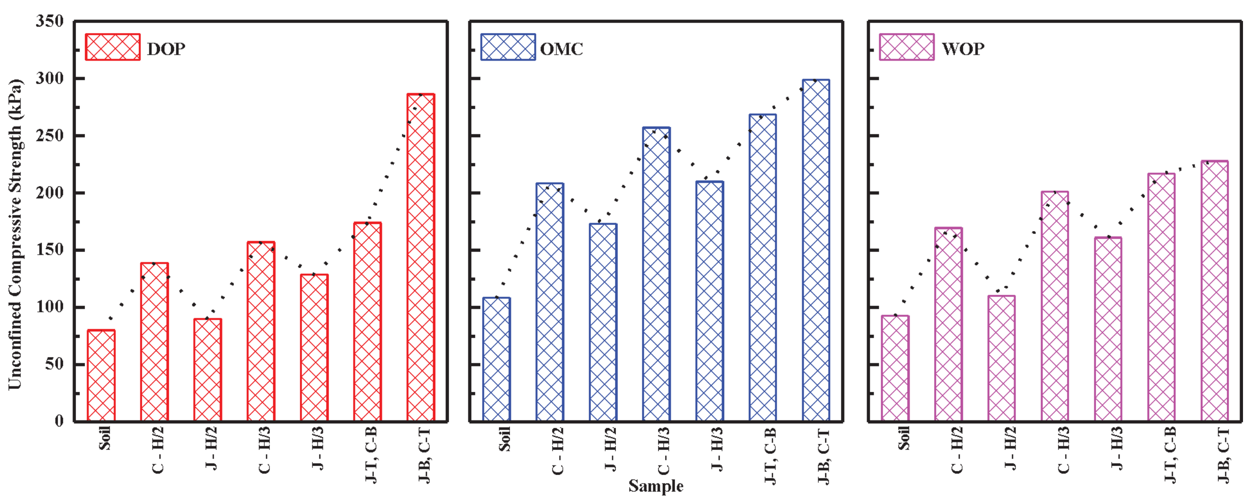

Figure 6: Comparison of maximum stress in UCC tests for different configurations

This superior performance can be attributed to the synergistic interaction between the two natural fibers: the stiffer jute positioned at the base provides strong enhanced confinement against vertical stresses, while the coir at the top improves energy dissipation and redistributes stresses more effectively across the soil mass. Such hybrid reinforcement behavior is consistent with the observations reported by references[18,28] emphasizing the importance of multi-material geotextile systems in enhancing confinement and load transfer.

Although the applied loading in the UCC test is axial compression, the internal stress within the specimen is not purely compressional. Under vertical loading, the soil undergoes lateral expansion due to Poisson's effect. This radial dilation mobilizes confinement force within the embedded geotextile layers, which act through membrane action and provide additional confinement. Similar behavior has been reported in triaxial studies on reinforced sand,[30] where reinforcement layers increased the peak stress by restraining lateral deformation. Therefore, the strength enhancement observed in the present study is attributed to the confinement effect induced by restriction of the lateral strain rather than direct tensile loading.

For single-layer reinforcement, placements at H/3 depth generally resulted in higher shear strength than at H/2 depth. This suggests that the reinforcement positioned closer to the critical shear stress zone mobilizes confinement more effectively. The mechanism is supported by references,[15,16] reporting that reinforcement effectiveness is strongly depth-dependent, with shallow placements activating greater confinement due to higher stress concentrations.

In all cases, unreinforced soil consistently exhibited the lowest shear strength, underlining the necessity of geotextile inclusion for performance improvement. The observed improvements align with the broader body of research on natural fiber geotextiles, where inclusion of coir, jute, or hybrid systems has been shown to enhance shear strength, stiffness, and load–settlement behavior in soft soils.[29] These findings confirm that natural fiber reinforcements, especially when configured in hybrid forms and optimized at OMC, can serve as an effective, sustainable alternative to synthetic reinforcements for soft ground improvement.

3.3 DIC-based soil deformation response under different configurations

Digital image correlation (DIC) was employed to quantify the displacement and strain behavior of reinforced and unreinforced soil specimens during unconfined compression, and the obtained results are detailed in **Table 3**. The unreinforced soil exhibited the maximum vertical displacement of 1.70 mm and the highest vertical strain of 0.0224 (2.24 %). Such pronounced deformation and lateral bulging are characteristic responses of cohesive soils subjected to unconfined compression, where no external lateral restraint is provided.

However, the magnitude of deformation observed in the untreated specimen highlights its limited resistance to radial expansion under axial loading. In the absence of reinforcement, the soil mass undergoes significant strain localization, leading to early bulging and reduced load-carrying efficiency. Similar deformation patterns have been documented in previous studies on unreinforced cohesive soils under UCC conditions.[30]

The inclusion of natural geotextiles significantly reduced both vertical displacement and strain, demonstrating the effectiveness of reinforcement in mobilizing confinement. For single-layer systems, coir reinforcement resulted in vertical strains of 0.0203 at H/2 and 0.0175 at H/3, indicating improved deformation control when the layer was placed closer to the critical shear zone. Jute-reinforced specimens showed vertical strains of 0.0192 at H/2 and 0.0213 at H/3, suggesting that jute performs more efficiently at mid-height due to its comparatively higher tensile strength. These results are in agreement with earlier studies on depth-dependent reinforcement behavior reported by references.[4,11,29] The findings confirm that both the type of natural fiber and the depth of placement strongly influence the degree of confinement mobilized within the soil mass.

The most effective deformation control was achieved using the hybrid reinforcement systems. The jute-bottom, coir-top (J-B, C-T) configuration exhibited the lowest vertical displacement (0.97 mm) and minimum vertical strain (0.0127 or 1.27 %), indicating superior resistance to axial compression and effective suppression of bulging. The jute-top, coir-bottom (J-T, C-B) arrangement also showed notable improvement with a vertical strain of 0.0162 (1.62 %), though its performance was inferior to the J-B, C-T system. The enhanced response

Table 3: Strain and displacement characteristics of soil at various reinforcement configurations

Configuration	Vertical displacement (mm)	Vertical strain	Shear strain
Coir H/2	1.54242	0.0203	0.3999
Coir H/3	1.33333	0.0175	0.3091
Jute H/2	1.4605	0.0192	0.2331
Jute H/3	1.61868	0.0213	0.2036
Jute-bottom, coir-top	0.96774	0.0127	0.0454
Jute-top, coir-bottom	1.23265	0.0162	0.2374
Soil (unreinforced)	1.70213	0.0224	0.0062

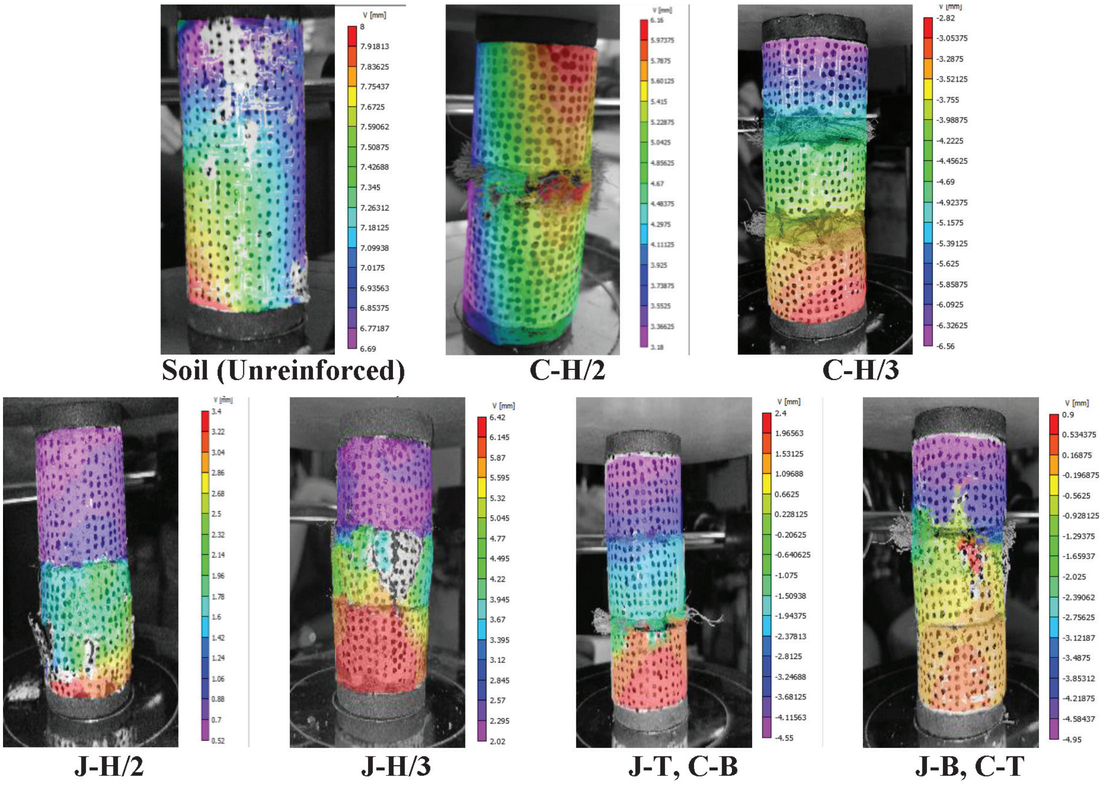

Figure 7: DIC-based visualization of failure modes and strain localization in soil under various reinforcement configurations

of the hybrid configuration is attributed to the combined action of stiff jute at the base, which effectively resists shear deformations near the failure zone, and the more ductile coir at the top, which aids in redistributing stresses and delaying strain localization. Similar synergistic effects of hybrid natural fiber systems were reported by references.[4,12,28]

Based on the corrected strain values, the deformation resistance of the tested configurations follows the order:

J-B, C-T > J-T, C-B > coir H/3 > jute H/2 > coir H/2 > jute H/3 > unreinforced soil. The DIC strain contours obtained at the optimum moisture condition (**Figure 7**) further substantiate this trend, with the unreinforced specimen displaying intense localized strain and pronounced bulging, while the reinforced specimens exhibit more diffuse strain fields and delayed failure. Among all configurations, the J-B, C-T system shows the most uniform strain distribution, confirming its superior confinement efficiency and deformation control capability. Similar DIC-based observations on suppression of shear band propagation were reported by references.[18,31]

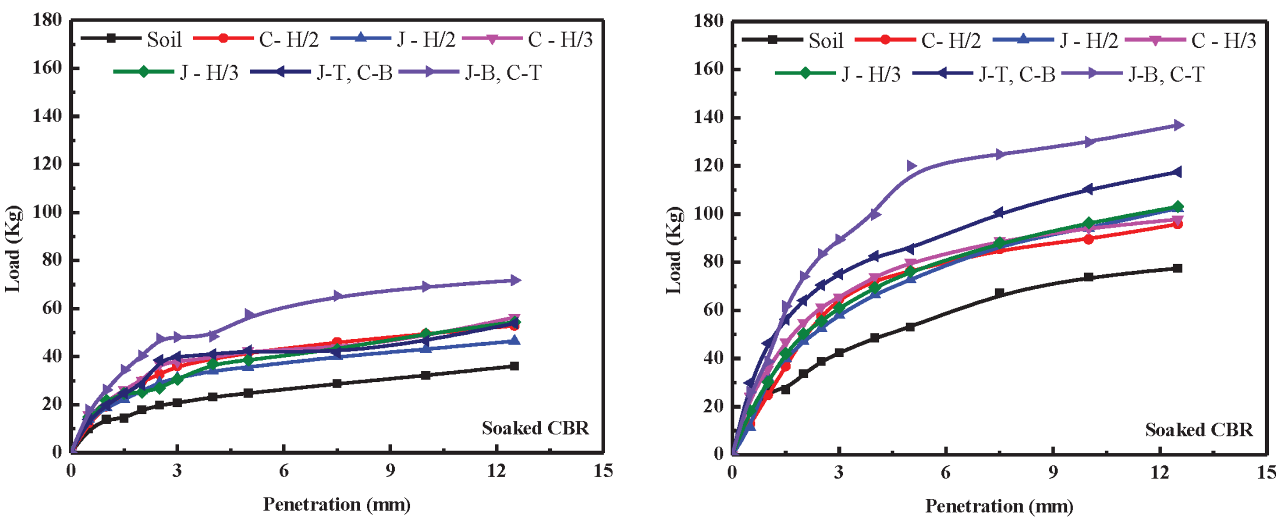

Figure 8: Comparison of load-penetration values for soil at OMC under soaked and unsoaked conditions

3.4 CBR soil response at the OMC under different configurations

The California Bearing Ratio (CBR) tests were conducted in accordance with the ASTM standard using the 2.5 mm penetration criterion,[32] revealing a clear improvement in the load-bearing response of the soil due to the natural geotextile reinforcement. The untreated soil exhibited a low CBR of 2.83 %, indicating poor subgrade strength. The CBR trends showed strong agreement with the findings of the UCC and DIC analyses, confirming that both reinforcement configuration and moisture condition significantly influence soil resistance (**Figure 8**). In all test conditions, unsoaked specimens recorded higher CBR values than soaked specimens, which can be attributed to the contribution of matric suction and stronger particle interlocking in the partially saturated state. After soaking, the unreinforced soil experienced a pronounced drop in CBR due to loss of suction and softening of the clay structure, a behavior commonly identified in cohesive subgrades.[33]

The introduction of coir and jute geotextiles markedly enhanced the CBR under both moisture conditions, demonstrating their effectiveness in improving strength and moisture resistance. A single coir layer placed at mid-height (H/2) almost doubled the CBR value. At H/2 depth, the CBR values increased to 4.19 % for coir and 3.84 % for jute. When the reinforcement was provided in two layers at H/3 depth, further enhancement was observed, with CBR values increasing to 4.49 % for coir and 4.05 % for jute. The superior performance of coir is mainly associated with its higher tensile strength, rougher surface texture, and greater water absorption capacity, which improve the soil–reinforcement interaction and stress transfer efficiency.

Among all reinforcement configurations, the hybrid system with jute at the bottom and coir at the top (J-B, C-T) exhibited the highest CBR under both soaked and unsoaked conditions, indicating its superior load-distributing capability. This behavior is attributed to the stiffer jute layer mobilizing membrane confinement effect within the active stress zone, while the coir layer placed near the surface contributes to better stress dispersion and reduced localized deformation. Comparable improvements in moisture-resistant performance of coir- and jute-reinforced subgrades were reported by references.[11,14]

The depth of reinforcement placement played a critical role in determining the CBR response. For both coir and jute, the reinforcement positioned at H/3 depth consistently produced higher CBR values than the placement at H/2, confirming that the reinforcement located closer to the zone of maximum shear stress is more effective in mobilizing confinement. This observation is in close agreement with the depth-dependent reinforcement behavior reported by references.[15,16] The overall ranking of CBR improvement across the tested configurations closely matched the trends obtained from UCC and DIC studies, highlighting the consistency of the reinforcement mechanism under different loading and testing conditions.

From a pavement design viewpoint, the enhancement in subgrade CBR directly translates into a reduction in the required thickness of flexible pavements. As per reference[34], pavement layer thickness is primarily governed by the subgrade CBR and design traffic level. The untreated soil, with a CBR of about 2.83 %, necessitated a relatively large total pavement thickness of approximately 55 cm for low-volume road applications. With coir reinforcement, the required thickness was reduced to 39 cm and 37 cm for placements at H/2 and H/3 depths, respectively. In the case of jute reinforcement, the thickness was reduced to 43 cm and 40 cm at H/2 and H/3 depths, respectively. A further reduction to 36 cm and 32 cm was achieved for the jute–top/coir–bottom and jute–bottom/coir–top hybrid systems, respectively, as reported in the last cited study.

The results clearly demonstrate that hybrid coir–jute reinforcement significantly improves bearing capacity, minimizes moisture-induced strength deterioration, and enables the design of thinner and more economical, flexible pavement sections in accordance with reference[34]. The close correspondence between the CBR response, UCC behavior, and DIC-based deformation patterns further confirms the robustness and practical reliability of the proposed reinforcement strategy for subgrade improvement applications.

4 CONCLUSIONS

This study evaluated the performance of single and hybrid coir–jute geotextile reinforcements in clayey soil using UCC, CBR, and DIC analyses under different compaction states. Based on the experimental results, the following conclusions are drawn:

The soil compacted at optimum moisture content (OMC) consistently exhibited higher UCC strength and CBR values compared to dry-of-optimum (DOP) and wet-of-optimum (WOP) conditions, confirming that OMC provides the most favorable soil structure for reinforcement mobilization.

The hybrid configuration with jute at the bottom and coir at the top (J-B, C-T) produced the highest strength improvement, achieving an approximately 45–55 % increase in unconfined compressive strength compared to unreinforced soil. The single-layer reinforcement placed at H/3 depth performed better than the placement at H/2, indicating that the reinforcement closer to the critical shear zone mobilizes greater confinement.

DIC measurements showed that the J-B, C-T system reduced vertical strain from 2.24 % (unreinforced soil) to 1.27 %, demonstrating effective suppression of bulging and strain localization. Hybrid reinforcement resulted in more uniform strain distribution compared to single-layer systems.

The untreated soil exhibited a CBR of 2.83 %, whereas reinforced configurations significantly improved both soaked and unsoaked CBR values. The J-B, C-T arrangement achieved the highest improvement, leading to a reduction in the required pavement thickness from approximately 55 cm (unreinforced) to 32 cm as per IRC:37-2018 guidelines.

The consistency between UCC strength gain, CBR enhancement, and DIC-based deformation control confirms that the hybrid coir–jute system provides effective confinement through membrane action and restriction of lateral strain.

Overall, the experimental evidence demonstrates that the jute-bottom, coir-top hybrid configuration positioned near the active stress zone delivers the most efficient improvement in strength and deformation resistance among the tested layouts. The multi-test validation framework adopted in this study establishes a clear performance hierarchy for reinforcement configurations and provides quantitative support for the optimized hybrid arrangement.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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