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A Study on the Reinforcement Effect of Geotextiles from Renewable Textile Fibers on the Interface of Natural Gravel and Silty Clay

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Article

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ABSTRACT

The textile industry is undergoing a transformation driven by sustainable development, seeking alternatives to petroleum-based products. This research investigates novel textile products derived from renewable fibers, evaluating their performance in geotechnical engineering as a sustainable alternative to conventional synthetics. We explore the reinforcement effect of nonwoven geotextiles fabricated from processed yarn and staple fibers of polylactic acid (PLA)—a biodegradable organic compound—and natural fibers such as jute and coir, which are sourced through agricultural methods similar to those used for cotton. The study focuses on the challenging interface between natural gravel and silty clay. Through large-scale direct shear tests, the performance of these advanced fiber products was quantified. Unlike traditional weaving, the nonwoven manufacturing process creates a unique fabric structure. All renewable geotextiles significantly enhanced the interface shear strength, with the PLA textile increasing it by up to 75%. This improvement is attributed to the application of advanced textile technology and materials science, resulting in a durable fabric with high frictional characteristics. The findings represent a significant advancement for both geotechnical engineering and the textile industry, demonstrating that bio-based and natural fibers can be engineered into high-performance materials, thus creating a new class of functional textiles.

KEYWORDS

textile technology, renewable fibers, sustainable development, geotextile, natural fibers

INTRODUCTION

In civil and geotechnical engineering, the construction of infrastructure such as roads, railways, and foundations often involves layering different types of soil and aggregate materials [1,2]. A common scenario is the placement of a granular base or subbase course, such as gravel, over a fine-grained subgrade like silty clay [3,4]. The interface between these two distinct materials is frequently a plane of mechanical weakness, susceptible to shear failure under traffic or structural loads [5]. The low shear strength of the silty clay subgrade, coupled with potential adverse effects from moisture variation, can lead to excessive deformation, rutting, and ultimately, structural failure [6,7].

For decades, geosynthetic materials—particularly geotextiles made from synthetic polymers such as polypropylene (PP) and polyester (PET)—have been successfully employed to address these challenges [8]. When placed at the interface, geotextiles perform several key functions, including separation, filtration, drainage, and reinforcement [9]. The reinforcement function is of primary importance for improving mechanical stability [10]. By enhancing the shear strength of the soil interface, geotextiles can increase the load-bearing capacity and service life of the structure [11]. The mechanism of reinforcement is complex, involving increased frictional resistance, interlocking of soil particles with the textile structure, and a tensioned membrane effect that helps distribute loads more effectively [12].

However, the widespread use of conventional geosynthetics has raised significant environmental concerns [13]. These materials are derived from finite petrochemical resources, and their production is energy-intensive. Furthermore, their high resistance to degradation means they persist in the environment for centuries after the service life of the structure, contributing to plastic pollution and complicating end-of-life management [14,15]. This has spurred a growing interest in developing sustainable and biodegradable alternatives from renewable resources.

Renewable textile fibers, both natural (e.g., jute, coir, flax) and bio-based polymers (e.g., polylactic acid—PLA), offer a promising pathway toward “green” geotechnical solutions [16,17]. Natural fibers are abundant, inexpensive, and biodegradable, possessing favorable mechanical properties such as high tensile strength and a rough surface texture that can enhance soil interaction [18–20]. PLA, derived from the fermentation of renewable resources such as corn starch, is a biodegradable thermoplastic that can be processed into fibers and nonwoven fabrics using conventional textile manufacturing techniques [21,22]. These materials have the potential to provide the necessary reinforcement during the critical early life of a structure and then biodegrade over time, returning to the natural ecosystem.

This research aims to investigate the reinforcement effect of geotextiles fabricated from renewable textile fibers on the shear behavior of a natural gravel–silty clay interface. The study focuses on quantifying the improvement in shear strength and understanding the underlying reinforcement mechanisms. Three types of nonwoven geotextiles, made from PLA, jute, and coir fibers, were produced and tested using a large-scale direct shear apparatus. By comparing the performance of these renewable geotextiles with the unreinforced interface, this study seeks to evaluate the feasibility of their use for soil interface reinforcement, quantify the enhancement in peak shear strength and interface friction angle, and analyze the load-deformation behavior and failure mechanisms of the reinforced interface, thereby providing a scientific basis for the design and application of sustainable geotextiles in geotechnical engineering. The findings are expected to contribute to the development of more environmentally responsible construction practices, aligning with global efforts toward a circular economy and sustainable development.

LITERATURE REVIEW

Shear Behavior of Soil–Geotextile Interfaces

The interaction between soil and geotextiles is a critical aspect of reinforced soil structure design. The interface behavior is typically characterized by its shear strength, which is a combination of adhesion and friction. For a geotextile placed between two dissimilar soils, such as a coarse aggregate and a fine-grained clay, the overall system strength is governed by the weakest of the interfaces: gravel–geotextile or clay–geotextile.

Numerous studies have investigated the shear behavior of soil–geosynthetic interfaces using direct shear and pull-out tests. The performance is influenced by many factors, including the properties of the geotextile (e.g., material, structure, thickness, roughness), the characteristics of the soil (e.g., particle size distribution, plasticity, density), and the testing conditions (e.g., normal stress, drainage conditions). Research has shown that nonwoven geotextiles generally exhibit better interface shear strength compared to woven ones, especially with coarse-grained soils, due to the increased opportunity for soil particles to embed into the three-dimensional fibrous structure—a phenomenon known as interlocking. The normal stress level is also a crucial parameter, as higher normal stresses typically lead to greater penetration of particles into the geotextile, resulting in a higher interface friction angle.

Reinforcement of Weak Subgrades

The use of geotextiles to reinforce unpaved roads and foundations built on weak subgrades is a wellestablished practice. The primary benefit of the geotextile is to prevent the mixing of the granular base course with the soft subgrade soil—a function known as separation. However, the reinforcement function is equally important. By developing tensile forces, the geotextile restrains the lateral movement of the aggregate base under load, which improves the confinement and stiffness of the base layer. This “tensioned membrane” effect helps to spread the applied load over a larger area of the subgrade, reducing the vertical stress and associated deformation. Studies using plate load tests and full-scale field trials have consistently demonstrated that geotextile reinforcement can significantly increase the bearing capacity and reduce the rut depth of unpaved roads, allowing for a reduction in the required thickness of the aggregate base course.

Geotextiles from Renewable Fibers

The exploration of natural and renewable fibers for geotechnical applications is not new, but it has gained significant momentum due to growing environmental awareness. Natural fibers such as jute, coir, and sisal have been traditionally used for temporary erosion control in the form of woven mats or blankets. These fibers possess high initial tensile strength and stiffness. For example, jute fibers have a tensile strength that can be comparable to that of polypropylene fibers. Their rough surface texture is advantageous for developing high frictional resistance with soil.

However, the primary challenge associated with natural fibers is their biodegradability and susceptibility to moisture. While their degradation is an environmental benefit in the long term, it must be controlled to ensure that the geotextile maintains its structural integrity for the required design life of the application. The rate of degradation depends on the fiber type and the environmental conditions (e.g., soil pH, moisture, microbial activity).

PLA represents a new generation of bio-based polymers that bridge the gap between natural fibers and conventional synthetics. PLA is produced from renewable resources and is fully biodegradable under industrial composting conditions. As a thermoplastic, it can be melt-spun into fibers and converted into nonwoven geotextiles with consistent and engineered properties. Research on PLA geotextiles is still emerging, but initial studies have shown their potential in applications requiring medium-term reinforcement, offering a more predictable degradation profile compared to natural fibers.

Research Gaps

While there is extensive literature on the reinforcement of soil with synthetic geotextiles, research on the interface behavior of geotextiles made from renewable fibers—particularly in the context of a gravel–silty clay system—is limited. Most studies on natural fiber geotextiles have focused on their use in erosion control or as reinforcement within a single soil type rather than at a bimaterial interface. Furthermore, a direct comparison of the reinforcement efficiency of different types of renewable fibers (natural vs. biopolymer) under controlled laboratory conditions is needed. This study aims to fill this gap by providing a systematic evaluation of the shear strength enhancement provided by PLA, jute, and coir geotextiles at a critical geotechnical interface, thereby contributing valuable data for the design and implementation of sustainable reinforced soil systems.

MATERIALS AND METHODS

Materials

Soils

- Natural Gravel: The coarse-grained material used was a crushed granitic gravel, classified as well-graded gravel (GW) according to the Unified Soil Classification System (USCS). Its properties are summarized in Table 1. A conceptual illustration of the soil particles is shown in Figure 1.
- Silty Clay: The fine-grained subgrade material was a natural clay, classified as a low-plasticity clay (CL) under the USCS. The descriptive term **silty clay** is used in this study to refer to its challenging engineering characteristics, characterized by a moderate plasticity index (18%) and relatively high maximum dry density (1.68 g/cm³), which contribute to its stiff consistency and low workability. Its index properties, determined according to ASTM standards, are also listed in Table 1.

Table 1. Geotechnical Properties of the Gravel and Silty Clay

Property	Gravel	Silty Clay	Standard
Specific Gravity	2.68	2.72	ASTM D854
D60 (mm)	15.2		ASTM D6913
D30 (mm)	6.8		ASTM D6913

D10 (mm)	0.9		ASTM D6913
Coefficient of Uniformity (Cu)	16.9		
Coefficient of Curvature (Cc)	3.38		
Liquid Limit (%)		42	ASTM D4318
Plastic Limit (%)		24	ASTM D4318
Plasticity Index (%)		18	ASTM D4318
Max. Dry Density (g/cm³)	2.15	1.68	ASTM D1557
Optimum Moisture Content (%)	6.5	18.5	ASTM D1557

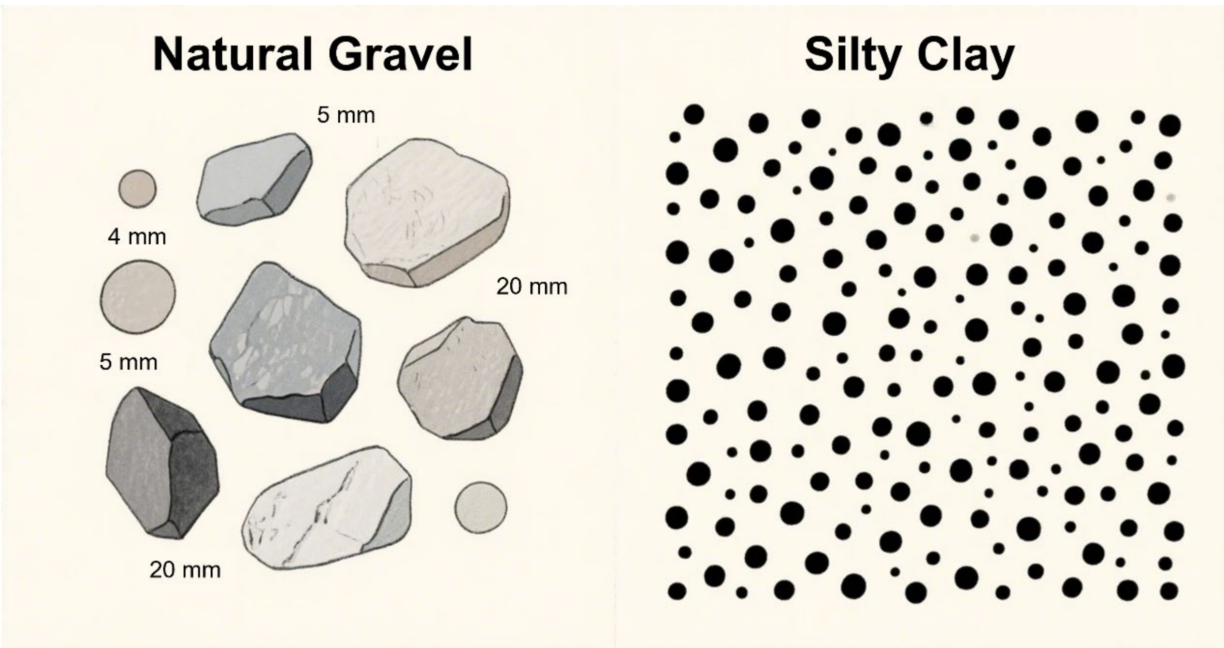

Figure 1. Conceptual illustration of the particle structures for the natural gravel (left) and silty clay (right)

Renewable Geotextiles

Three types of nonwoven geotextiles were fabricated from renewable fibers:

PLA Geotextile: Made from PLA staple fibers (6 dtex, 60 mm length) using a needle-punching process.

Jute Geotextile: Made from 100% natural jute staple fibers using needle-punching.

Coir Geotextile: Made from 100% natural coir (coconut) fibers using needle-punching.

All geotextiles were manufactured to have a comparable mass per unit area to ensure a fair comparison. The key physical and mechanical properties of the geotextiles are presented in Table 2.

Table 2. Properties of the Renewable Geotextiles

Property	PLA Geotextile	Jute Geotextile	Coir Geotextile	Standard
Mass per Unit Area (g/m²)	400 ± 20	410 ± 25	420 ± 30	ASTM D5261
Nominal Thickness (mm)	3.5	4.2	5.0	ASTM D5199
Tensile Strength (kN/m)	15.2	13.8	11.5	ASTM D4595
Tensile Elongation (%)	55	25	35	ASTM D4595

The target mass per unit area of approximately 400 g/m² was chosen as it is a representative value for medium-weight nonwoven geotextiles commonly used in soil reinforcement and stabilization applications. All geotextiles were specifically manufactured for this study to meet this target, ensuring a fair comparison between the different fiber types. The resulting variations in thickness are a direct consequence of the inherent properties of the fibers themselves (e.g., the bulkiness of coir versus the finer PLA fibers). These properties are hypothesized to directly influence the reinforcement effect; for example, greater thickness can enhance the potential for mechanical interlocking with the gravel, while higher tensile strength is crucial for mobilizing the tensioned membrane effect under shear loading.

Experimental Setup

A large-scale direct shear apparatus with a shear box measuring 300 mm × 300 mm in plan and 200 mm in height was used for the interface shear tests. The size of the box was chosen to minimize scale effects, with the box width being more than 15 times the maximum particle size of the gravel (Dmax = 19 mm). The apparatus was capable of applying normal stresses up to 1,000 kPa and shearing the sample at a controlled displacement rate.

Sample Preparation

For each test, the lower half of the shear box was filled with the silty clay. The clay was prepared at its optimum moisture content (18.5%) and compacted in three layers to achieve 95% of its maximum dry density. The surface of the clay layer was meticulously prepared to be flush with the shear plane. Any excess material was first carefully removed using a wire saw, staying slightly above the final intended elevation. The final surface was then created by carefully shaving off the remaining soil with a sharpened steel straightedge, which removed the thin layer of soil potentially disturbed by the wire saw and ensured a smooth, uniform, and undisturbed plane for testing.

For the reinforced tests, the geotextile specimen (300 mm × 300 mm) was placed directly on top of the compacted clay surface. For the unreinforced tests, this step was omitted.

The upper half of the shear box was then positioned, and the gravel was placed on top of the clay (or geotextile) and compacted to a dense state.

Testing Procedure

All tests were performed in a climate-controlled laboratory with the temperature maintained at 20 ± 2 °C and a relative humidity of 50 ± 5%. The direct shear tests were conducted following the principles of ASTM D5321.

Consolidation: A predetermined normal stress of 50, 100, or 150 kPa was applied to the sample. These stress levels were chosen to represent typical pressures found in low-volume roads and shallow foundations. The sample was allowed to consolidate under the target normal stress until the rate of vertical settlement decreased to less than 0.01 mm/min, ensuring primary consolidation was complete.

Shearing: The sample was sheared at a constant displacement rate of 1.0 mm/min. Under the selected shear rate and the difference in permeability of the layered materials, the gravel layer tends to drain, and the clay layer has limited drainage, forming an assumption of non-uniform drainage conditions.

Data Acquisition: The shear force, horizontal displacement, and vertical displacement were recorded continuously throughout the test using a computerized data acquisition system. Shearing continued until a horizontal displacement of 45 mm (15% of the box length) was reached.

To ensure the reliability and repeatability of the results, each unique test configuration (four interface types × three normal stress levels) was conducted twice, for a total of n = 2 repetitions per configuration. The overall testing sequence of these 24 trials was randomized to mitigate potential biases arising from time-dependent or batch effects. Although the number of repetitions was limited to n = 2 due to the labor-intensive nature of the large-scale testing setup, the large shear box dimensions (300 × 300 mm) minimize boundary effects and provide a more representative elementary volume compared to standard small-scale apparatus. Furthermore, the meticulous sample preparation procedure ensured high homogeneity between specimens, resulting in consistent shear behavior across the trials.

RESULTS

Shear Stress–Displacement Behavior

The shear stress versus horizontal displacement curves for the unreinforced and reinforced interfaces under a normal stress of 100 kPa are presented in Figure 2.

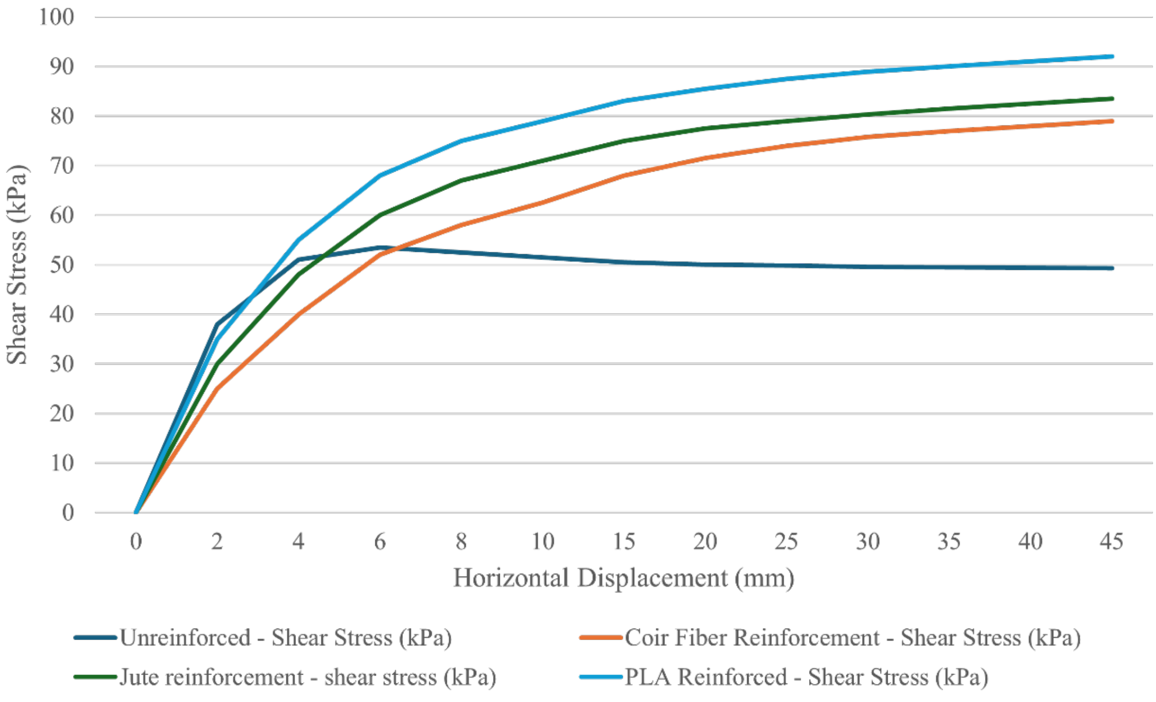

Figure 2. Shear stress–displacement behavior of unreinforced and reinforced interfaces under a normal stress of 100 kPa

The unreinforced interface exhibited a relatively low peak shear strength, which was reached at a small displacement (around 5–7 mm), followed by slight strain-softening behavior. This indicates a brittle failure, likely dominated by sliding along the smooth clay surface.

In contrast, all reinforced interfaces showed a significant increase in shear strength. The curves for the geotextile-reinforced samples did not exhibit a distinct peak, instead showing strain-hardening behavior where the shear stress continued to increase with displacement. This ductile response suggests a different failure mechanism, where the geotextile effectively transfers stress and prevents a localized failure plane from forming. Among the renewable geotextiles, the PLA-reinforced interface mobilized the highest shear resistance, followed by the jute and then the coir geotextiles. The same general trends were observed for the tests conducted at 50 kPa and 150 kPa normal stress.

Peak Shear Strength and Reinforcement Efficiency

As the reinforced interfaces exhibited strain-hardening behavior without a distinct peak, a consistent criterion was needed to define the peak shear strength. Therefore, the mobilized shear strength at 10% displacement was adopted as the representative peak strength for design purposes—a horizontal displacement of 30 mm (10% of the shear box length). This approach is not arbitrary but aligns with common practice in geotechnical interface testing and is consistent with guidelines in standards such as ASTM D5321. This level of deformation is often considered a serviceability limit in field applications, thus representing a practical and relevant measure of the maximum mobilized shear resistance for design purposes. The peak shear strength envelopes for all test series are plotted in Figure 3, according to the Mohr-Coulomb failure criterion.

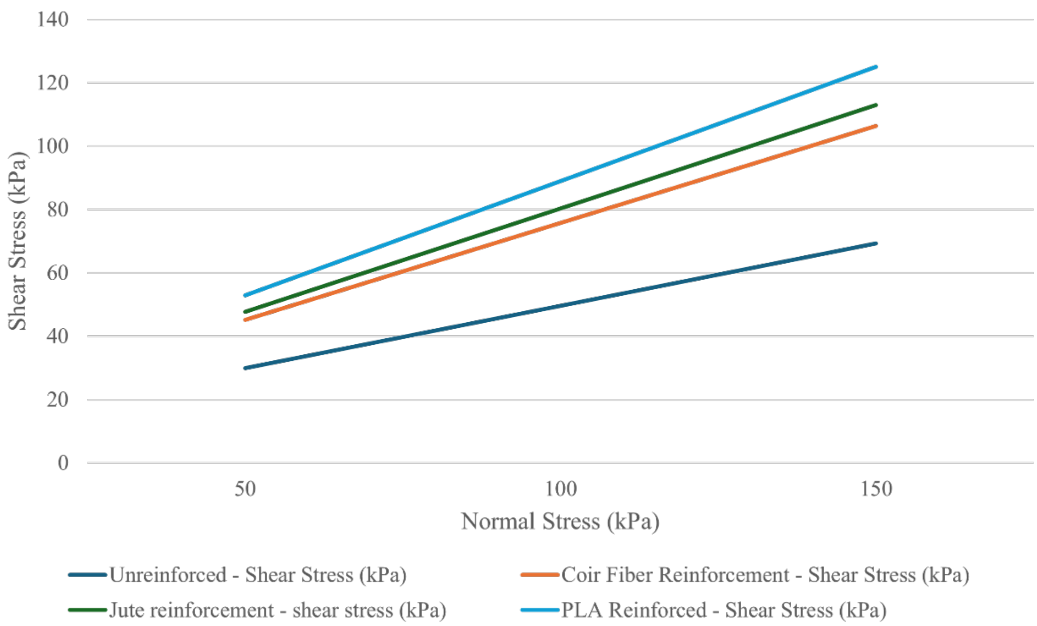

Figure 3. Mohr-Coulomb failure envelopes for the unreinforced and reinforced gravel–clay interfaces

The inclusion of the geotextiles resulted in a substantial increase in the shear strength parameters. The apparent cohesion (c) and interface friction angle (δ) for each configuration, determined from the Mohr-Coulomb failure envelopes shown in Figure 3, are summarized in Table 3. Each pair of c and δ values represents the single best-fit linear failure envelope derived from the set of three tests conducted at normal stresses of 50, 100, and 150 kPa. The PLA geotextile provided the most significant improvement, increasing the interface friction angle from 21.5° for the unreinforced case to 35.8°. Jute and coir geotextiles also yielded notable increases in the friction angle to 33.1° and 31.5°, respectively.

Table 3. Interface Shear Strength Parameters Derived from Tests at 50, 100, and 150 kPa Normal Stress

Interface Configuration	Apparent Cohesion, c (kPa)	Interface Friction Angle, δ (°)
Unreinforced	10.2	21.5
Reinforced with Coir	14.5	31.5
Reinforced with Jute	15.1	33.1
Reinforced with PLA	16.8	35.8

The reinforcement efficiency can also be quantified by the ratio of the reinforced peak shear strength to the unreinforced peak shear strength. At a normal stress of 100 kPa, the PLA, jute, and coir geotextiles increased the peak shear strength by 79%, 62%, and 53%, respectively, demonstrating a clear and significant reinforcement effect.

DISCUSSION

The experimental results clearly indicate that geotextiles made from renewable fibers can effectively reinforce the interface between gravel and silty clay. The observed increase in shear strength and the change from brittle to ductile failure behavior can be attributed to several key, interconnected mechanisms. While all three geotextiles engage these reinforcement mechanisms, their differing properties (Table 2) suggest the degree to which each mechanism contributes varies. For instance, the enhanced mechanical interlocking is likely most pronounced in the jute and coir geotextiles. Their significantly greater thickness and coarser fiber structure provide a more three-dimensional, compressible matrix for the gravel particles to embed into, creating substantial initial resistance to sliding. However, the superior overall performance of the PLA geotextile, despite being the thinnest, indicates that the tensile reinforcement mechanism is dominant. With the highest tensile strength and a comparatively high stiffness (inferred from its strength-to-elongation ratio), the PLA geotextile can more effectively mobilize tensile forces as shear displacement occurs. This creates a stronger "tensioned membrane" that better confines the gravel particles and distributes the load. While the natural fiber geotextiles also provide tensile restraint, their lower strength means this mechanism is less impactful compared to the PLA. This suggests a trade-off: while the natural fibers excel in passive interlocking due to their bulk, the engineered PLA excels in active tensile reinforcement due to its superior material properties, ultimately leading to the highest measured shear strength.

The interface friction angles achieved with the renewable geotextiles in this study, ranging from 31.5° to 35.8°, are highly competitive with those reported in the literature for conventional PP nonwoven geotextiles at similar aggregate–clay interfaces. This suggests that, from a purely mechanical standpoint, renewable geotextiles—particularly PLA-based ones—can be considered technically viable alternatives to synthetic geotextiles for this type of reinforcement application.

The findings of this research have significant implications for sustainable construction practices. From an economic standpoint, a full cost-benefit analysis is beyond this study's scope, but a qualitative discussion is warranted. While the raw material costs for natural fibers such as jute and coir are often low, particularly as agricultural by-products, these savings can be offset by processing and logistics. Currently, the market price for PLA is higher than for conventional petroleum-based polymers such as polypropylene. However, a crucial economic consideration is the full lifecycle cost. Conventional synthetic geotextiles can incur significant end-of-life expenses for removal and landfilling, alongside the unquantified environmental costs of plastic pollution. By biodegrading in situ, the renewable geotextiles discussed here eliminate these future liabilities. Although a detailed life cycle cost analysis (LCCA) is required to verify the economic feasibility, the elimination of end-of-life disposal costs suggests that renewable geotextiles could offer long-term value, particularly when environmental externalities are factored in. The ability to use effective, biodegradable geotextiles derived from renewable resources offers a solution to the long-term environmental persistence of conventional geosynthetics. For applications such as temporary access roads, landscape engineering, or use in environmentally sensitive areas, these materials are ideal. They can provide the required mechanical function during the critical construction and early service life phases. Over time, as the soil consolidates and gains strength naturally, the geotextile can biodegrade, minimizing the long-term environmental footprint. The use of natural fibers such as jute and coir, which are often agricultural by-products, also supports rural economies in developing countries and contributes to a circular economy model. While a quantitative analysis of durability and biodegradation was beyond the scope of this mechanical study, these characteristics are critical for defining the appropriate application for each material. The expected service life under prolonged moisture and microbial activity in a real-world scenario directly influences material selection. Natural fibers such as jute and coir are known to degrade relatively quickly in soil, with a functional lifespan typically ranging from 6 to 24 months. This makes them highly suitable for short-term applications, such as temporary access roads or erosion control, where reinforcement is needed only until the surrounding soil consolidates and gains its own strength. In contrast, PLA has a much slower and more predictable degradation profile, primarily driven by hydrolysis. In typical soil conditions, it can be expected to retain its structural integrity for several years, making it a viable candidate for semi-permanent applications where a medium-term service life is required. Therefore, the excellent mechanical performance demonstrated in this study must be considered in conjunction with these differing degradation timelines to select the appropriate material for a given geotechnical design life. Additionally, the direct shear tests were performed under a limited range of normal stresses (50–150 kPa). While this range is representative of applications such as low-volume roads, it may not fully capture the material's behavior under higher confining pressures found in other structures, such as high embankments. It is known that soil–geotextile interfaces can exhibit nonlinear shear strength envelopes at higher stresses. Therefore, the linear failure criteria presented should be applied with caution outside of the tested stress range, and future work should investigate this behavior at broader stress levels to develop more comprehensive design parameters. It should be noted that the shear rate of 1.0 mm/min adopted in this study, while consistent with similar comparative studies on interface behavior, is relatively fast for the silty clay component. This rate likely induced partially undrained conditions within the clay subgrade, potentially generating excess pore water pressure that could slightly reduce the measured interface strength. Therefore, the significant reinforcement benefits observed in this study can be considered a conservative estimate compared to fully drained conditions that might develop over the long term.

CONCLUSION

This study provides compelling evidence of the reinforcement effect of nonwoven geotextiles made from renewable fibers at a natural gravel–silty clay interface. The inclusion of these geotextiles, whether from biopolymers such as PLA or natural fibers such as jute and coir, significantly enhances the shear strength of the interface. The reinforcement fundamentally changes the failure mode from brittle sliding to a more ductile, strain-hardening behavior, indicating the effective mobilization of reinforcement mechanisms such as mechanical interlocking, enhanced friction, and tensile restraint. Notably, the performance of the renewable geotextiles, in terms of interface friction and shear strength improvement, is comparable to that of conventional synthetic nonwoven geotextiles, establishing them as a technically viable and environmentally superior alternative for certain geotechnical applications. This research supports the ongoing shift toward the use of renewable materials in construction, paving the way for more sustainable and eco-friendly geotechnical solutions. Future work should focus on the long-term in situ performance and biodegradation characteristics of these materials to establish comprehensive design guidelines.

Availability of Data and Materials

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

Author Contributions

Jiang Liu, Junting Chen and Chenglong Zhang designed the study; all authors conducted the study; Bin Kuang and Ji Tian collected and analyzed the data. Shimao Le and Zheng Wang participated in drafting the manuscript, and all authors contributed to critical revision of the manuscript for important intellectual content. All authors gave final approval of the version to be published. All authors participated fully in the work, took public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or completeness of any part of the work were appropriately investigated and resolved.

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Conflict of Interest

The authors declare no conflict of interest.

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