Experimental and Numerical Investigation of the Shear Behavior of Jute Fiber-Reinforced Lateritic Gravel for Road Applications.

Abstract:

Background: Lateritic gravels are the main road-construction materials in tropical regions, but their mechanical performance remains limited under traffic loading and climatic variations; reinforcement with natural fibers, particularly jute, offers a durable and eco-friendly improvement pathway.

Methods: A lateritic gravel from Avlamè was reinforced with 0.75% jute fiber (1 cm length). Unconsolidated undrained (UU) triaxial tests were carried out on both the raw and the reinforced material, complemented by numerical modeling based on the Mohr-Coulomb and Drucker-Prager failure criteria.

Results: Experimental cohesion increases from 115.8 kPa (raw material) to 188.0 kPa (reinforced material), i.e. +62%, while the internal friction angle slightly decreases from 29.6° to 28.6°. Numerical simulations confirm this trend (cohesion: 108.4 to 188.8 kPa, i.e. +74%; friction angle: 30.5° to 28.4°).

Conclusion: Incorporating 0.75% jute fiber markedly improves the cohesion and stiffness of Avlamè lateritic gravel, with a slight decrease in internal friction angle, confirming the potential of natural fibers as a technical and eco-friendly solution for improving road materials.

Keywords: cohesion, internal friction angle, jute fiber, lateritic gravel, numerical modeling, triaxial test.

1. Introduction

The development of road infrastructure is a key lever for the economic and social development of developing countries. Pavement performance and durability depend in particular on the mechanical properties of the materials used in their various layers. In sub-

Saharan Africa, and particularly in Benin, lateritic materials constitute an important source of local material for road works owing to their availability and their proximity to construction sites. Previous studies have notably shown the value of characterizing local lateritic gravels in order to assess their suitability for use in road infrastructure[1], [2], [3].

Despite their availability, lateritic materials exhibit variability in their geotechnical and mechanical properties depending on their origin, grain-size composition, moisture state, and compaction conditions. This variability can limit their use in certain road applications and justifies the use of improvement techniques capable of increasing their mechanical performance. Conventional methods based on hydraulic binders or crushed granite are effective [4], [5], [6], but the search for more environmentally friendly solutions adapted to local resources has led to the development of new reinforcement techniques.

In this perspective, soil reinforcement with natural fibers is attracting growing interest in geotechnical engineering. Plant fibers represent a potentially attractive alternative to conventional reinforcing materials owing to their renewable nature, availability, and low cost. Several literature reviews devoted to soil reinforcement with natural and synthetic fibers highlight the key role of fiber type, dosage, and length[7], [8], [9]. These observations, derived from specific experimental studies, confirm that optimizing these parameters governs the improvement of the mechanical performance of treated soils [10], [11], [12].

Several studies also confirm the value of natural fibers for improving the mechanical behavior of soils. Soleimani-Fard et al. [13] showed that the presence of randomly distributed fibers can significantly modify the shear strength of soils, particularly under unsaturated conditions. A study devoted to natural fibers in geotechnical applications further highlights their potential for soil reinforcement and the development of more sustainable infrastructure [14].Similarly, Medina-Martinez et al. [15]highlight the value of various natural fibers, notably jute, sisal, coconut fiber, bamboo, and sugarcane bagasse, for improving the geotechnical properties of soils. Jute fiber is of particular interest in this approach. Its availability, biodegradability, and mechanical properties make it a material that can be exploited in soil reinforcement techniques. Experimental studies have specifically investigated the use of jute fiber to improve the mechanical properties of geotechnical soils, while recent research on natural fibers confirms the growing interest in these materials for sustainable infrastructure applications[16], [17].

The study of the behavior of lateritic gravels reinforced with jute fibers under triaxial loading therefore appears necessary to better understand the reinforcement mechanisms and to assess their potential for use in road infrastructure. The present study aims to evaluate the influence of incorporating 0.75% jute fiber of 1 cm length on the shear behavior of a lateritic gravel, based on an experimental and numerical approach. The experimental approach relies on triaxial tests to determine the shear-strength parameters of both the natural and the reinforced material. The numerical approach is then based on the Mohr–Coulomb and Drucker–Prager criteria, in order to compare the parameters obtained and to assess the ability of these two models to represent the failure behavior of the material over the stress range studied.

2. Materials and methods

2.1. Materials

2.1.1. Lateritic gravel

The material studied comes from the village of Demè, in the Avlamè district, Zogbodomey commune, in southern Benin. This commune occupies the southern part of the Abomey plateau, about 150 km north of Cotonou, between 6°56' and 7°08' north latitude and 1°58' and 2°24' east longitude. It covers nearly 825 km², i.e. about 15.74% of the surface area of the Zou department, at an average elevation of around 120 m. Its administrative boundaries are formed, to the north, by the communes of Bohicon and Za-Kpota, to the south, by Lalo and Toffo, to the east, by Covè and Zagnanado, and to the west, by the commune of Agbangnizoun (Figure 1) [8].

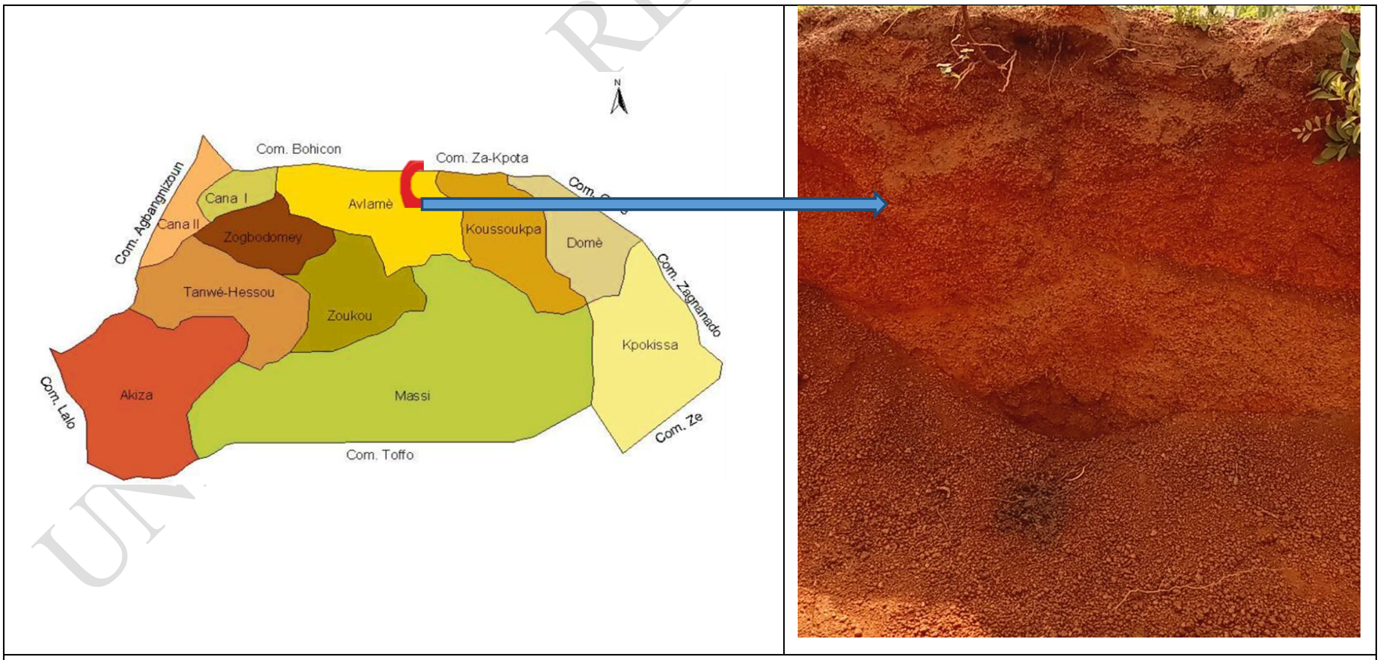

Figure 1. Geographic location of the Avlamè lateritic deposit, Zogbodomey commune, Benin.

The geotechnical characteristics of the raw lateritic gravel from Avlamè are presented in Table 1 below:

Table 1. Geotechnical characteristics of the raw lateritic gravel

Sample	Dmax	AG	AG	AG	LL	PI	GTR	ϒs	OM	γd	w	Swelling	CBR	CBR

		2mm	0.08mm	0.63mm			(2023)						95%	100%
GL	31.5	43.5	32	29	42	18	I2	2.75	0.23	2.19	8.8	0.04	34	58

Note: AG = grain-size fractions passing at the indicated sieve size; LL = liquid limit; PI = plasticity index; GTR = French soil classification for earthworks (2023 edition); ϒs = specific gravity of solids; OM = organic matter content; γd, w = maximum dry density and optimum water content at Modified Proctor; CBR = California Bearing Ratio.

2.1.2. Jute fibers

In this study, the jute fibers were obtained from bags collected from traders at the Dantokpa market in southern Benin, where they are commonly used for packaging and transporting agricultural produce such as onions, rice, or millet. Once these bags were acquired, they were cut to extract the constituent threads, which were then trimmed to a uniform length of 1 cm before being incorporated into the material. Beyond its technical interest, this approach fits into a strategy of valorizing a locally available agricultural by-product while relying on a low-environmental-impact resource.

(a) Jute bags *(b) Extraction of threads* *(c) Cutting of jute fibers* *(d) Cut jute fiber*

Figure 2. Jute fibers obtained from jute bags.

2.1.3. Composite mixture: lateritic gravel improved with 1 cm jute fibers dosed at 0.75%

The composite material investigated in this study is the lateritic gravel reinforced with jute fibers. The jute fibers were cut into 1 cm lengths and incorporated into the lateritic gravel at a dry-mass content of 0.75%. This formulation was selected based on preliminary characterization results and mechanical-performance tests carried out on various fiber-reinforced mixtures. The 0.75% fiber content was identified as the optimal formulation given the improvement in mechanical properties and bearing capacity of the lateritic gravel [8], [18], [19].The selected composite was also assessed against the conventional requirements for pavement materials set by CEBTP. The mechanical characteristics of the composite are summarized in Table 2 below:

Table 2. Characteristics of the lateritic gravel reinforced with 0.75% jute fibers

Characteristics	**Value**
Jute fiber length	1 cm
Fiber content	0.75 %
Maximum dry density	2.17 t/m³
Optimum water content	7.80 %
CBR at 95% OPM	66.0 %
Linear swelling	0.06 %

2.2. Equipment for geotechnical testing

The equipment used for the geotechnical tests complies with the recommendations of standard NF EN ISO 17892-8 for the UU triaxial test.

(a) Manual core sampler (b) Water tank (c) Moulds

(d) Impermeable disc (e) Membranes (f) Stretcher

Figure 3.Sampling equipment.

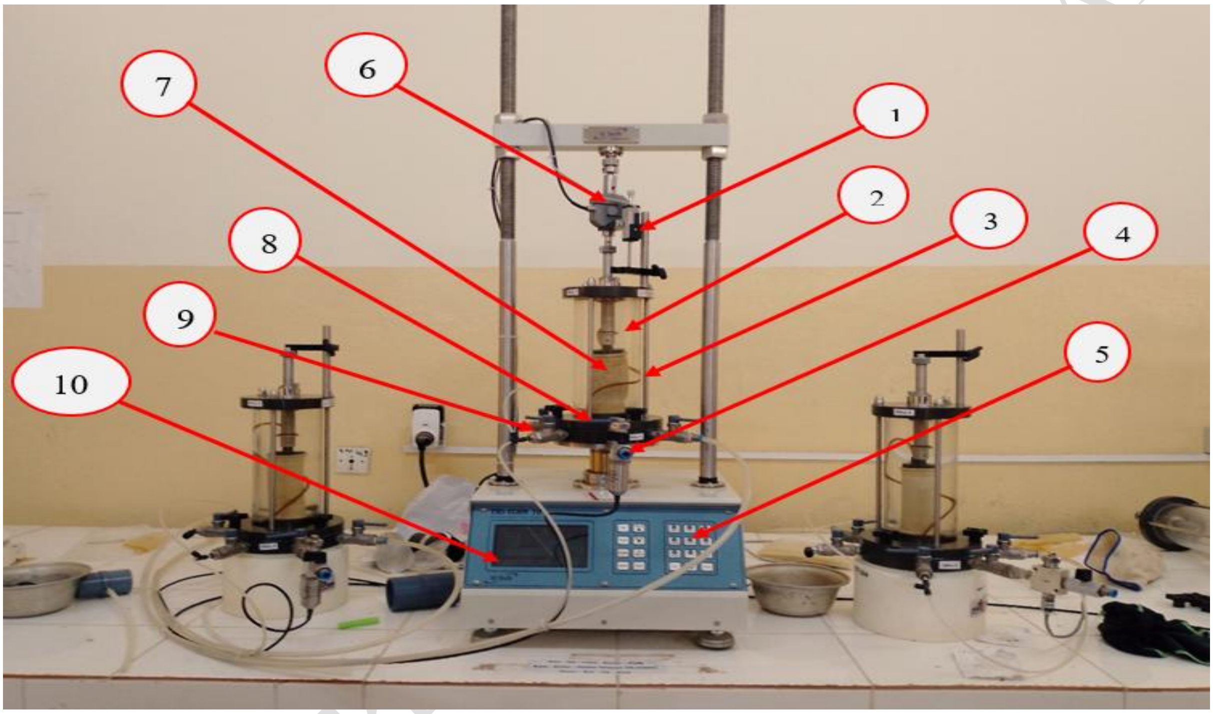

Figure 4. Triaxial test equipment.

1: Displacement transducer

2: Confining water inside the triaxial cell

3: Triaxial cell

4: Back-pressure device

5: Triaxial press control unit

6: Load cell

7: Specimen under shearing

8: Triaxial cell base

9: Confining-pressure transducer

10: Triaxial press.

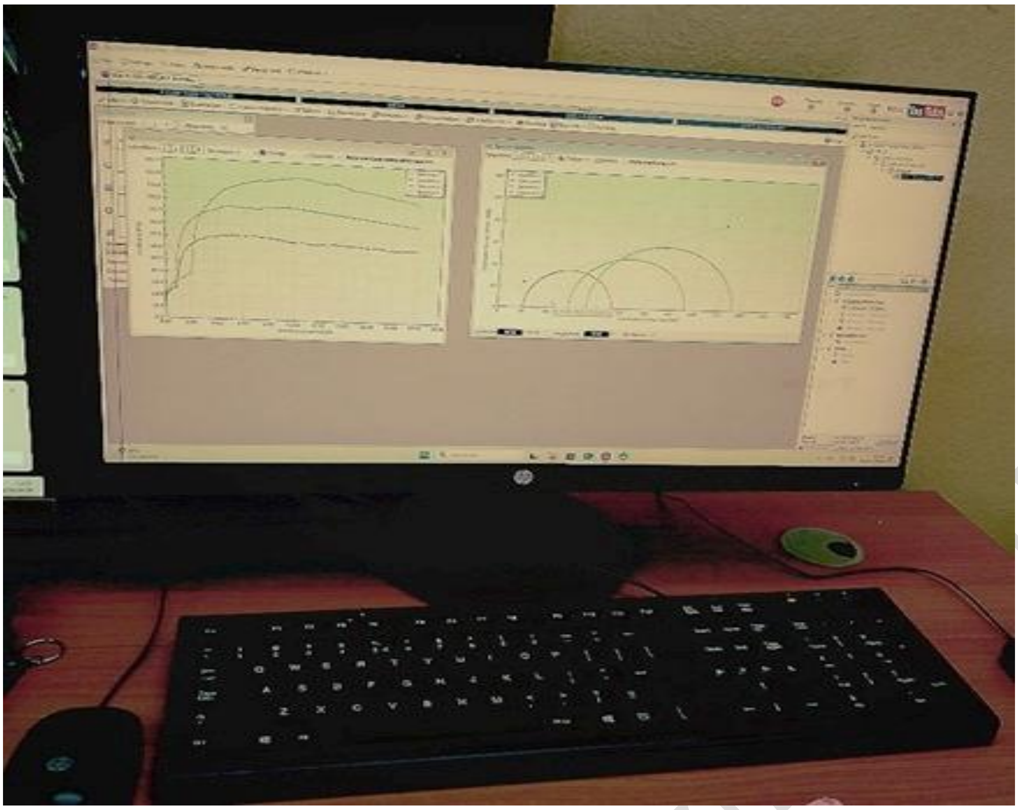

Figure 5. Computer for digital processing and test-data acquisition.

2.3. Experimental method (numerical models)

The methodological approach adopted in this study is organized around the following steps:

- Prepare specimens of raw and reinforced material;
- Core, from these specimens, cylindrical samples ready for the shear test;
- Carry out triaxial tests on the different materials, in accordance with the standard cited above;
- Determine the shear-strength parameters (cohesion and internal friction angle) both experimentally and numerically, using the Mohr-Coulomb and Drucker-Prager criteria;
- Discuss and compare the results obtained from the experimental and numerical approaches used in this study.

Figure 6. Specimen preparation steps.

Specimen preparation is carried out in several successive steps. The material is first compacted in a mould at the energy level corresponding to the target optimum (95% of OPM), then carefully demoulded to preserve its structural integrity. The resulting specimen is then kept in an airtight bag or container to maintain its optimum water content, before being cored: an operation that consists of extracting, from the core of the compacted specimen, a cylindrical sample of standardized dimensions, ready for direct use in the triaxial test. This coring step is critical, as it governs the homogeneity and representativeness of the material tested.

Once the cored specimens have been obtained, the shear tests on the material are carried out.

Figure 7. Triaxial tests on specimens.

The triaxial test is carried out following the unconsolidated undrained (UU) procedure, suited to the short-term behavior of the material. The cored specimen is first wrapped in a watertight latex membrane, then placed in the triaxial cell between the two porous stones or rigid platens ensuring uniform stress transmission. A confining pressure σ_3, kept constant throughout the test, is then applied through the cell fluid, reproducing the initial isotropic stress state experienced by the material in place.

An increasing axial load is then applied at a controlled strain rate until specimen failure, allowing the corresponding deviatoric stress $\Delta\sigma$ to be measured. This operation is repeated on several identical specimens subjected to different confining pressures, so as to obtain as many (σ_3, σ_1) pairs at failure as needed to determine the shear-strength parameters of the material, presented in the next section.

2.3.1. Mohr-Coulomb model

The Mohr-Coulomb criterion is a classical method used in geotechnical engineering to determine the point at which a material begins to fail under external stress. This criterion relates the normal stress and the shear stress on the potential failure surface. The key equation describing the Mohr-Coulomb criterion is:

where:

:shear stress at failure.

normal stress.

: cohesion of the material.

: internal friction angle.

This equation shows how the strength of a material depends both on its intrinsic cohesion and on the friction angle.

The Mohr-Coulomb model is based on the normal and shear stresses to which a material is subjected. At any point in a soil, there exist planes on which the shear stress is zero. The normal stresses on these planes are called principal stresses, denoted σ1 (major) and σ3 (minor).

Indeed, in a triaxial test, the soil specimen is first uniformly "squeezed" by a confining pressure σ3. This is the minor principal stress. An additional vertical load, the deviatoric stress Δσ, is then applied. The total vertical stress therefore becomes the sum of the initial confining pressure and this additional load. This vertical stress is the major principal stress, σ1.

The major principal stress is the sum of the minor principal stress and the deviatoric stress.

where Δσ is the deviatoric stress.

The Mohr-Coulomb criterion is particularly suited to modeling the failure of granular soils (sands) as well as cohesive soils under long-term drained conditions (clays and silts). The yield function, which defines the plasticity threshold, is expressed by the following relation (Figure 8):

where σ1 and σ3 are the extreme principal stresses.

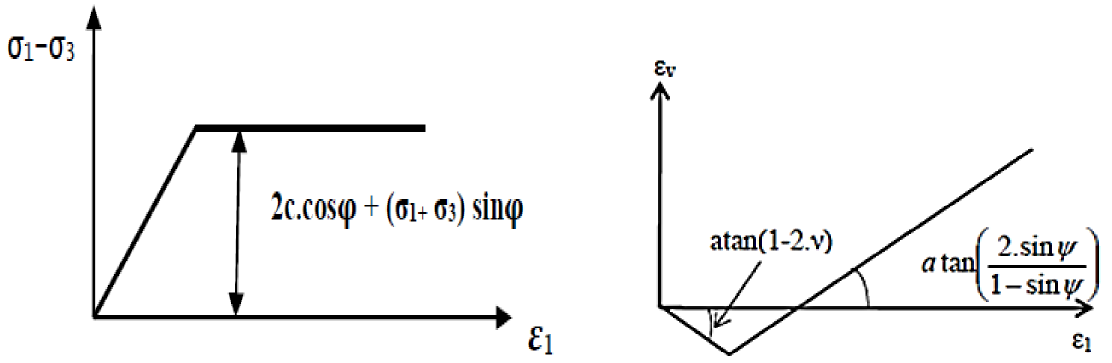

Figure 8. Mohr-Coulomb model.

Experimentally, the determination of the shear parameters c and φ relies on applying this equation at the failure state. When a soil specimen reaches failure along a given stress path, its stress state satisfies the condition f(σij) = 0.

By carrying out several tests (several triaxial tests on identical specimens subjected to different confining pressures), one obtains as many equations as measured failure states. This system of equations, overdetermined once the number of tests exceeds the number of unknowns (c and φ), is solved using the least-squares method, which allows the parameters c and φ of the soil to be determined optimally.

This automatable approach offers significant practical value: it dispenses with manually plotting Mohr circles and with the subjective graphical estimation of the failure envelope, while ensuring mathematical rigor equivalent to that of the physical approach.

2.3.2. Drucker-Prager model

This is an elastoplastic model without hardening. The elastic part of the constitutive law is linear and isotropic, characterized by the Young's modulus E and Poisson's ratio ν.

The failure criterion is given by the expression:

= 0 (4)

where I_1 is the first stress invariant and J_2 the second invariant of the stress deviator. These invariants are expressed as:

= ;since (confining pressure applied under isotropic conditions)

; Avec ; (5)

To feed the numerical model with the classical geotechnical parameters (c, φ), mathematical analogies are established between the Mohr-Coulomb and Drucker-Prager criteria to relate the parameters α and k to the cohesion c and the friction angle φ

Under axisymmetric triaxial conditions (σ2 = σ3), the analogy between the two criteria leads to the following relations:

and (6)

The inverse relations, allowing the intrinsic parameters to be deduced from α and k, are written as follows:

and (7)

Under plane-strain conditions (ε2 = 0); typical of a retaining-wall or road-trench calculation and assuming an associated flow rule, the analogy leads to the following simplified relations:

and (8)

3. Results

3.1. Presentation of triaxial test results on the materials

3.1.1. Raw lateritic gravel

The triaxial test results obtained on the raw lateritic gravel specimens are shown as stress strain curves and Mohr circles. Table 3 below summarizes the results data for the raw lateritic gravel.

Table 3. Triaxial test data for the raw lateritic gravel

Raw lateritic gravel				
Designation	**σ1(kPa)**	**σ3(kPa)**		
Specimen 1	532.77	50	241.385	291.385
Specimen 2	511.82	100	205.91	305.91
Specimen 3	992.25	200	396.125	596.125

The Mohr circles obtained from these tests are as follows:

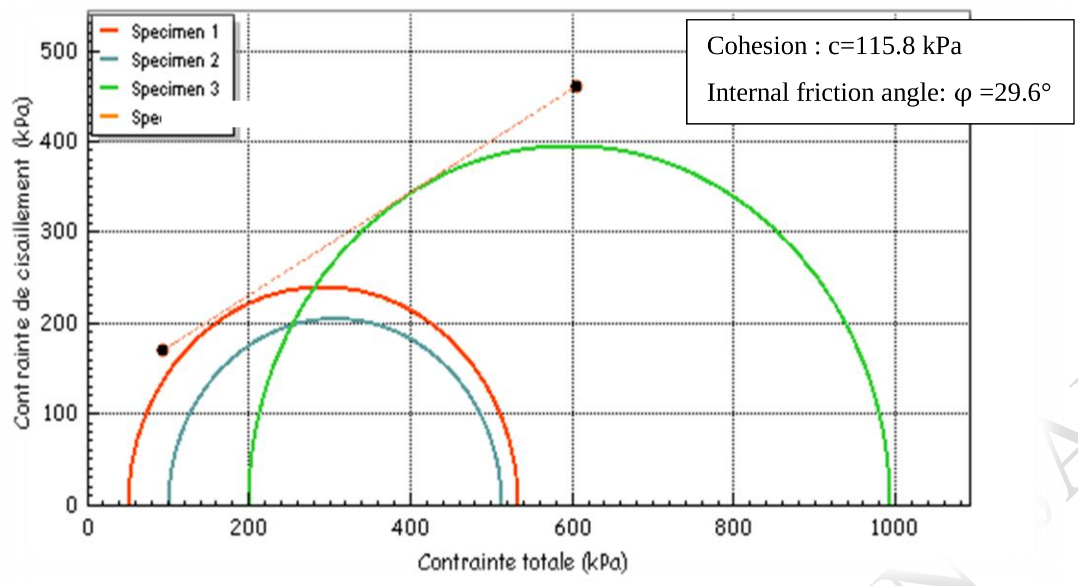

Figure 9. Shear stress–normal stress curves for the raw lateritic gravel.

Interpretation of the Mohr circles yields a cohesion of 115.8 kPa and an internal friction angle of 29.6° for the raw lateritic gravel. At a confining pressure of 200 kPa, the shear stress at failure is estimated at 360 kPa, corresponding to a normal stress of about 430 kPa. These parameters reflect good shear strength and indicate the stability of the material's internal structure, which is an asset for its use in pavement layers. The values obtained remain consistent with the orders of magnitude generally reported for lateritic gravels used in road construction.

Figure 10 shows the three stress-strain curves corresponding to the different confinement levels.

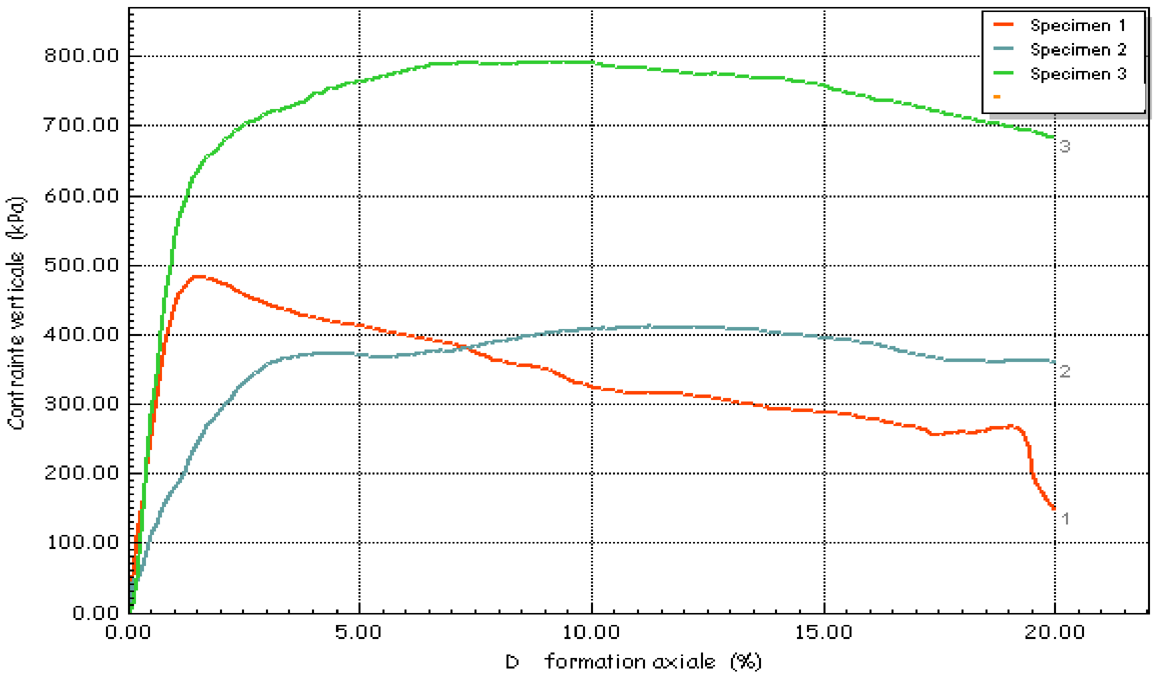

Figure 10. Stress-strain curve for the raw lateritic gravel.

Analysis of Figure 10 shows that the maximum deviatoric stresses recorded are 411.82 kPa, 482.77 kPa, and 792.25 kPa respectively, for peak strains of 11.32%, 1.61%, and 9.53%. The increase in maximum deviatoric stress with confinement level confirms the classical behavior of granular materials, for which shear strength increases with confining pressure, consistent with the Mohr-Coulomb failure criterion. The small strain observed at peak for the 50 kPa test reflects relatively brittle failure, while the larger strains for the other two tests at 100 and 200 kPa (11.3% and 9.5%) indicate more ductile behavior.

3.1.2. Lateritic gravel reinforced with jute fibers

To evaluate the effect of incorporating jute fibers on the mechanical behavior of the lateritic gravel, UU triaxial tests were also carried out on the composite material under confining pressures of 100, 200, and 400 kPa. The results obtained are presented in Table 4.

Table 4. Triaxial test data for the lateritic gravel reinforced with 0.75% jute fibers (1 cm)

Lateritic gravel reinforced with 0.75% jute fibers				
Designation	σ1 (kPa)	σ3(kPa)		
Specimen 2	914.89	100	407.445	507.445

Specimen 3	1501.05	200	650.525	850.525
Specimen 4	1759.3	400	679.65	1079.65

Figure 11 shows the Mohr circles established from the triaxial test results. These form the basis for determining the material's failure parameters.

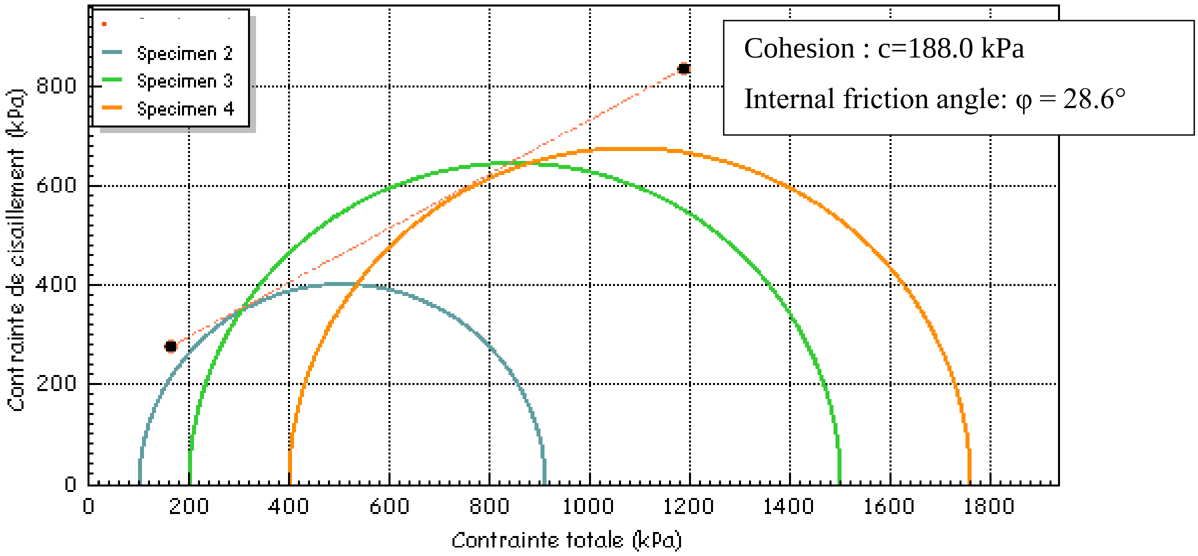

Figure 11. Shear stress–total stress curves for the lateritic gravel reinforced with 0.75% jute fibers (1 cm).

Interpretation of the Mohr circles yields a cohesion of 188 kPa and an internal friction angle of 28.6° for the composite material, for a shear stress at failure of 610 kPa and a normal stress of 774 kPa. Compared to the raw material (115.8 kPa and 29.6°), this evolution shows a substantial increase in cohesion (+62%), while the friction angle remains virtually unchanged (relative decrease of 1°). This behavior reflects the bridging effect exerted by the jute fibers between soil particles, which limits crack propagation and improves the cohesive strength of the material, without significantly altering the inter-granular friction mechanism.

Figure 12 shows the stress–strain curves of the composite material obtained under three confinement levels. These curves allow the influence of confining pressure on the strength and deformation mode of the material to be analyzed.

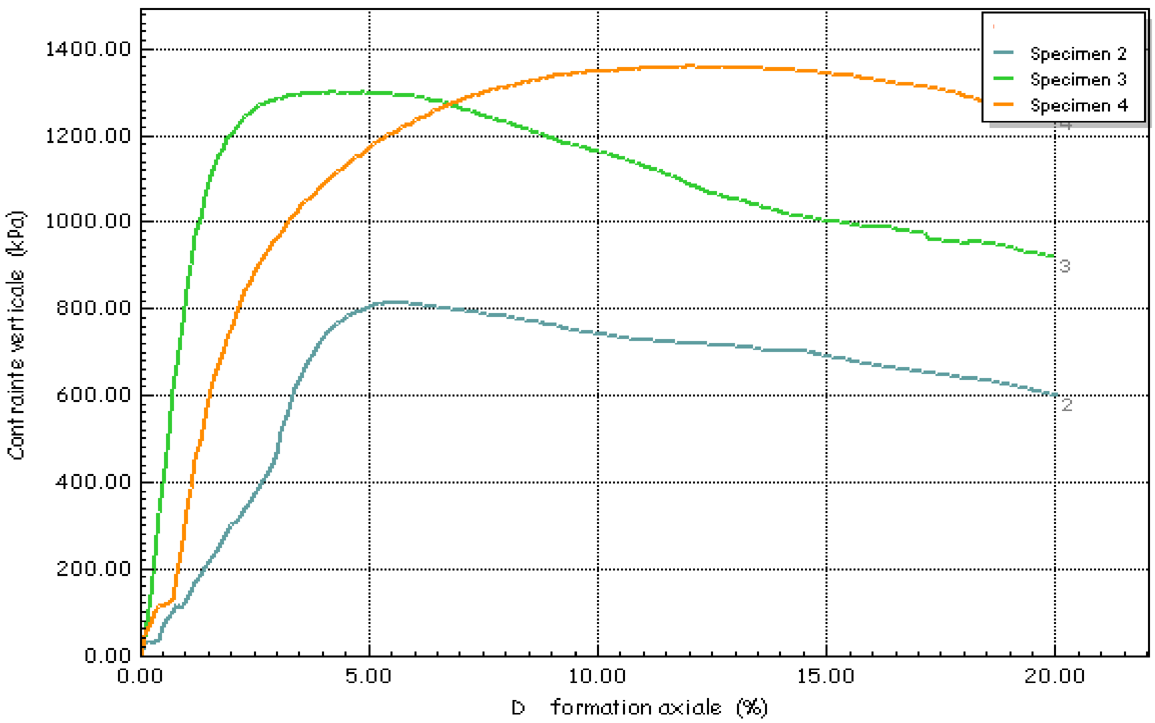

Figure 12. Stress-strain curve for the lateritic gravel reinforced with 0.75% jute fibers (1 cm).

Analysis of Figure 12 shows that the maximum deviatoric stresses reach 814.9 kPa, 1301.1 kPa, and 1359.3 kPa, for peak strains of 5.6%, 4.2%, and 12.1% respectively, reflecting a markedly increased capacity of the composite material to withstand shear loading, regardless of the confinement level.

Figure 13 illustrates a comparative summary of the cohesion values of the raw lateritic gravel and the composite material. The observed increase highlights the beneficial effect of jute-fiber incorporation on the cohesion of the material.

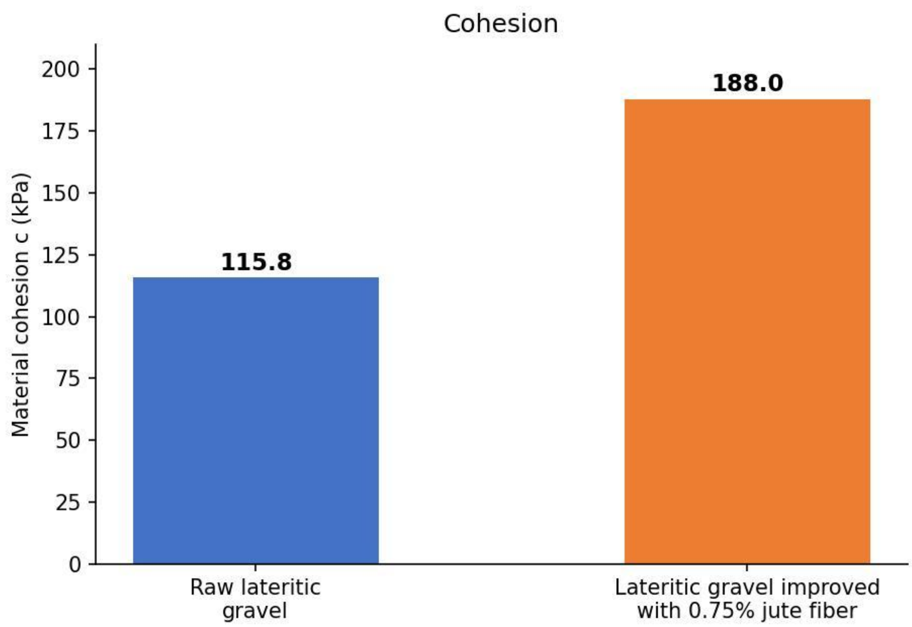

Figure 13. Variation of material cohesion.

3.2. Estimation of the intrinsic parameters c and φ

3.2.1. From the Mohr-Coulomb numerical model

Using the Mohr-Coulomb numerical model, the intrinsic parameters of the material are summarized in the table below:

Table 5. Parameters c and φ from the Mohr-Coulomb model

Mohr-coulombmodel							
Désignations		σ1 (kPa)	σ3(kPa)			(°)	c (kPa)
Raw lateritic gravel	Specimen 1	532.77	50	582.77	482.77	30.52	108.45
	Specimen 3	992.25	200	1192.25	792.25		
Lateritic gravel with jute fiber	Specimen 2	914.89	100	1014.89	814.89	28.41	188.80
	Specimen 4	1759.3	400	2159.3	1359.3		

Applying the Mohr-Coulomb model to the experimental results allowed the intrinsic characteristics of the two materials to be determined. For the raw lateritic gravel, the cohesion (c) and friction angle (φ) are respectively 108.45 kPa and 30.52°. For the jute-fiber-improved material, these parameters give values of 188.8 kPa for cohesion and 28.4° for friction angle.

3.2.2. From the Drucker-Prager numerical model

Using the Drucker-Prager numerical model, the intrinsic parameters of the material are summarized in the table below:

Table 6. Parameters c and φ from the Drucker-Prager model

Drucker-Prager model									
Designation		σ1 (kPa)	σ3(kPa)					(°)	c (kPa)
Raw lateritic gravel	Specimen 1	532.77	50	632.77	77 688.89	0.2353	129.87	30.52	108.45
	Specimen 3	992.25	200	1 392.25	209 220.02				
Lateritic gravel with jute fiber	Specimen 2	914.89	100	1 114.89	221 348.37	0.2176	227.86	28.41	188.80
	Specimen 4	1759.3	400	2 559.30	615 898.83				

Applying the Drucker-Prager model allowed the intrinsic shear-strength parameters of the two materials studied to be determined. For the lateritic gravel in its natural state, the internal friction angle and cohesion are 30.52° and 108.45 kPa respectively. In contrast, the material reinforced with jute fibers shows an internal friction angle of 28.40° and a cohesion of 188.80 kPa.

4. Discussion

The triaxial tests show that incorporating 0.75% jute fiber of 1 cm length substantially modifies the shear behavior of the lateritic gravel. For the natural material, cohesion and internal friction angle are 108.4 kPa and 30.52° respectively. After reinforcement, cohesion reaches 188.8 kPa, an increase of 74.2%, while the internal friction angle slightly decreases to 28.41°. The strength improvement is therefore mainly associated with the increase in the cohesive component. These observations are consistent with the work of Dossou[20]on the Avlamè lateritic gravel.

This evolution can be attributed to the interaction between the fibers and the particles of the lateritic matrix. During shearing, the fibers can mobilize tensile forces and restrict relative particle movement, thereby contributing to stress transfer and delaying the localization of failure. This reinforcement mechanism has been highlighted by Gray & Ohashi[21]and Maher & Gray[22], who showed that randomly distributed fibers can increase the shear strength of granular materials. The triaxial tests of Michalowski and Čermák [23]also confirm the positive influence of fibers on the strength and deformation capacity of reinforced granular materials.

The slight decrease in friction angle observed in the present study is not inconsistent with these results. Indeed, adding fibers does not necessarily lead to an increase in the internal friction angle (φ). Yetimoglu and Salbas[24]showed that fiber reinforcement mainly improves the overall strength of the material, without a systematic increase in friction angle. Similarly, Consoli et al.[25]showed, from triaxial tests, that the contribution of fibers to strength depends on the stress level and the loading path.

The effect observed in this study is particularly interesting given the use of jute fiber. Wang et al.[17]also reported an improvement in the mechanical characteristics of a soil reinforced with jute fiber, confirming the potential of this natural fiber as a geotechnical reinforcement element.

Finally, the parameters obtained from the Mohr-Coulomb and Drucker-Prager criteria show very good agreement for both materials. This closeness indicates that the two formulations provide a consistent representation of the failure behavior over the stress range explored. The Drucker-Prager criterion, proposed by Drucker and Prager[26]for the plastic analysis of soils, can thus constitute a suitable formulation for the numerical modeling of the materials studied. In the present study, the use of jute fiber achieves a significant strength improvement while valorizing a renewable plant material.

5. **Conclusion**

This study evaluated the influence of incorporating 0.75% jute fiber of 1 cm length on the shear behavior of a lateritic gravel intended for road applications. The analysis was carried out using triaxial tests and complemented by an interpretation based on the Mohr–Coulomb and Drucker–Prager failure criteria.

The experimental results show that jute-fiber incorporation mainly improves the cohesive component of shear strength. Cohesion thus increases from 115.8 kPa for the raw lateritic gravel to 188.0 kPa for the reinforced material, an increase of about 62%. In contrast, the internal friction angle remains of the same order of magnitude, going from 29.6° to 28.6° according to the graphical approaches considered. This evolution suggests that the effect of the fibers is mainly associated with fiber–soil interactions, fiber anchoring within the granular matrix, and stress transfer during shearing.

The analysis based on the Mohr–Coulomb and Drucker–Prager criteria leads to trends similar to those observed experimentally. The parameters derived from the modeling notably show a cohesion increase of about 74%, accompanied by a moderate decrease in internal friction angle. The good agreement in trends between the two approaches indicates that these formulations consistently represent the failure behavior of the material over the stress range studied. These results also provide a useful basis for the subsequent use of these parameters in numerical simulations of pavement-layer behavior.

Overall, the results obtained show that using 0.75% jute fiber is a promising route for improving the mechanical behavior of lateritic gravels. The value of this approach lies not only in the strength gain achieved, but also in the possibility of valorizing a renewable plant resource and developing reinforcement solutions adapted to local materials. Further work, particularly on long-term behavior, the durability of the fibers within the lateritic matrix, the influence of moisture conditions, and validation of the material at pavement scale, would nonetheless be necessary before its use in road infrastructure can be generalized.

6. Acknowledgments

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