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(Research Article)

Formulation of a composite road material based on lateritic gravel from Avlamè (Benin) reinforced with jute fibers

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Abstract

The modernization of transportation infrastructure is a key factor in economic and social development, particularly in developing countries in sub-Saharan Africa. The increasing scarcity of high-quality lateritic gravel and rising traffic volumes necessitate the improvement of available local materials. This study aims to formulate a composite material using lateritic gravel from Avlamè, reinforced with jute fibers, in order to meet the technical specifications required for pavement base courses. The methodological approach adopted consists of conducting Proctor and CBR tests on specimens of unprocessed lateritic gravel and on the material incorporating fibers of lengths 0, 1, 2, and 3 cm. For the optimal fiber length thus identified, fiber contents of 0.25%, 0.50%, 0.75%, 1%, and 1.25% were tested. The results show that 1-cm-long jute fibers, incorporated at an optimal dosage of 0.75% by mass, enable a CBR of 69.5% to be achieved, representing a 104.4% increase compared to the untreated gravel. The study highlights the technical and environmental benefits of plant fibers as an eco-friendly alternative to conventional stabilizers for road infrastructure in tropical regions.

Keywords: Lateritic Gravel; Jute Fibers; Composite Material; CBR

1. Introduction

The boom in global agricultural production, which has been particularly pronounced in sub-Saharan Africa, has been accompanied by a growing use of jute bags as packaging material for agricultural products (onions, grains, legumes, oilseeds). At the end of their life cycle, these bags are most often discarded, piled up in landfills, or burned in the open. In many developing countries, agricultural solid waste is left in the environment or burned in an uncontrolled manner, causing air pollution and greenhouse gas emissions. This situation calls for recovery solutions capable of transforming this waste stream into a useful resource.

Furthermore, lateritic soils constitute one of the most abundant and accessible geotechnical resources in tropical and intertropical regions [1]. However, their direct use in road construction faces limitations: low bearing capacity, sensitivity to water, swelling and shrinkage under hydrological cycles, and high compressibility [2, 3]. These constraints systematically require pretreatment, the environmental impact and cost of which hinder infrastructure development in developing countries. The addition of cement as a stabilizer, while effective, generates a significant environmental footprint due to CO_2 emissions during its manufacture and application [4]. The use of granite aggregate to improve soil bearing capacity has yielded satisfactory results [3, 5, 6]. However, the extraction and processing of this aggregate require costly procedures and cause environmental impacts. For example, the use of explosives to break up bedrock generates vibrations, shock waves, dust emissions, and significant noise pollution.

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The incorporation of plant fibers into clay matrices offers a solution to both of these problems simultaneously. Numerous studies have demonstrated the effectiveness of this reinforcement on various soil types. Natural fibers are recognized as effective and environmentally friendly for soil reinforcement, and many studies have highlighted the influence of fiber content on the mechanical strength of reinforced soils [7–10]. In the specific case of jute fiber, its random incorporation into a soil mixture improves the CBR index and the bearing capacity of the material [11–13].

Despite these advances, the use of fibers extracted from jute sacks—an eco-friendly material readily available in agricultural production areas—as a reinforcing agent for lateritic gravel in road construction remains largely unexplored. The overall objective is to formulate a clay-matrix composite material reinforced with jute fibers that meets the regulatory requirements for the base layers of flexible pavements. Experimentally, we will characterize the Avlamè lateritic gravel in its raw state and then evaluate the effect of fiber length and dosage on the CBR index to optimize the composite formulation.

2. Material and methods

2.1. Materials

2.1.1. Lateritic gravel

The lateritic gravel used in this study was collected from Avlamè, located in the municipality of Zogbodomey, Zou Department, in central Benin (Figure 1). This commune is located between 6°56’ and 7°08’ north latitude and 1°58’ and 2°24’ east longitude, approximately 150 km from Cotonou, in the southern part of the Abomey Plateau [14]. The samples were collected in accordance with standard XP P94-202 [15] and air-dried prior to analysis.

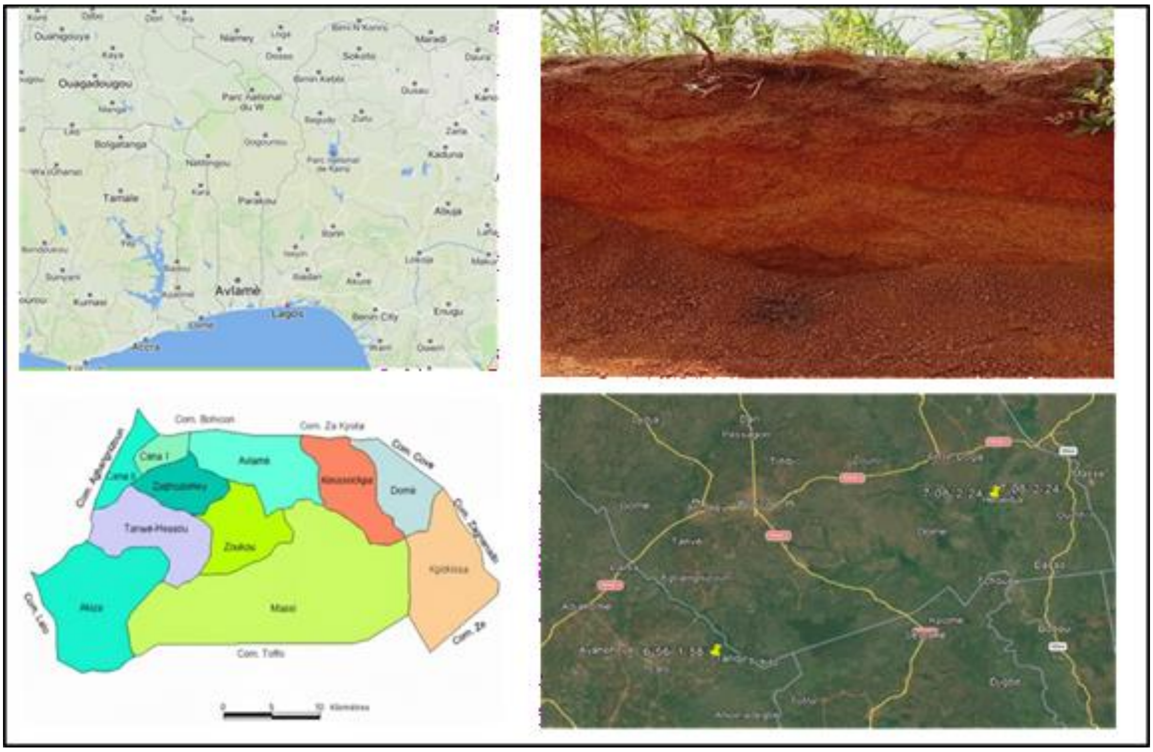

Figure 1 Geographic location of the Avlamè laterite deposit, Zogbodomey municipality, Benin

2.1.2. Jute Fibers

For the purposes of this study, the jute fibers used were sourced from jute bags collected from merchants at the Dantokpa Market (southern Benin). These bags are used for the transport and storage of agricultural products (onions, rice, millet, etc.). After acquisition, the bags were cut open to extract the fibers, which were then cut into regular lengths of 1 cm, 2 cm, and 3 cm. The choice of these lengths is based on previous studies [11, 12, 16, 17] that explored similar ranges for improving the mechanical properties of soils.

Figure 2 Steps for extracting fibers from jute bags

2.1.3. Equipment for Geotechnical Testing

The equipment used for geotechnical testing complies with the recommendations of the following standards:

- NF P 94-056, 1996 [18]. Soils: Investigations and Tests—Particle Size Analysis—Dry Sieving Method After Washing (Figure 3 (a));
- NF P 94-068, 1998 [19]. Soils: Investigation and Testing—Measurement of the Methylene Blue Adsorption Capacity of a Soil or Clay Material—Determination of the Methylene Blue Value of a Soil or Clay Material by Spot Test;
- XP P 94-047, 1998 [20]. Soils: Investigation and testing – Determination of the weight percentage of organic matter in a material – Calculation method;
- NF P 94-093, 2014 [21]. Soils: Investigation and testing. Determination of compaction parameters for a material. Modified Proctor test (Figure 3 (c));
- NF EN ISO 17892-12, 2018 [22]. Soils: Investigation and testing. Determination of Atterberg limits (Figure 3 (b));
- NF P 94-078, 1997 [23]. Soils: Investigation and testing. CBR index after immersion; Immediate CBR index (Figure 3 (c)).

Figure 3 Equipment for Geotechnical Testing

2.2. Experimental Methods

2.2.1. Characterization Tests on Raw Lateritic Gravel

Geotechnical characterization tests were conducted in accordance with the standards cited in §2.1.3. Samples were collected in accordance with the standard cited in §2.1.1. Each test was performed on two separate samples to ensure the representativeness of the results.

2.2.2. Mix Formulation Protocol

The formulation of the lateritic gravel + jute fiber mixtures was conducted in two successive stages, following the similar methodological approach proposed by Singh and Bagra [24] and Kumar et al. [11].

Step 1: Optimization of fiber length: The fiber content was kept constant at 1% by mass, with four different lengths (0, 1, 2, and 3 cm). Modified Proctor and CBR tests were performed on each mixture to identify the length offering the best mechanical performance.

Step 2: Optimization of fiber content: The identified optimal length is retained, and the incorporation rate is varied according to the following values: 0; 0.25; 0.50; 0.75; 1.00; and 1.25% by mass. As before, modified Proctor and CBR tests are performed on each mixture to identify the optimal dosage.

The mixtures were prepared manually. The jute fibers are first incorporated into the dry soil and mixed to achieve uniform distribution. Water was then added gradually while continuing to mix, until the optimal moisture content determined by the Proctor test was reached. The mixture was mixed for a few more minutes to ensure the homogeneity of the composite before compaction.

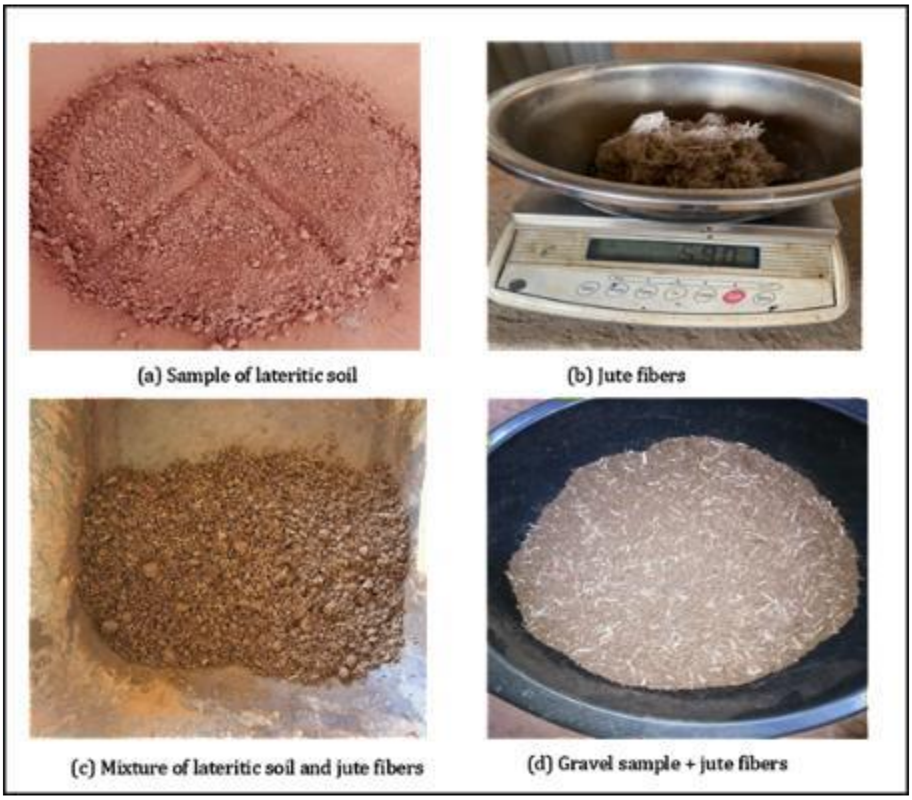

Figure 4 Collection of samples of lateritic gravel mixed with jute fibers

3. Results and discussion

3.1. Characterization of Raw Lateritic Gravel

3.1.1. Particle Size Analysis

The results of the sieve analysis of the two samples of lateritic gravel from Avlamè are illustrated by the particle size distribution curves in Figure 5.

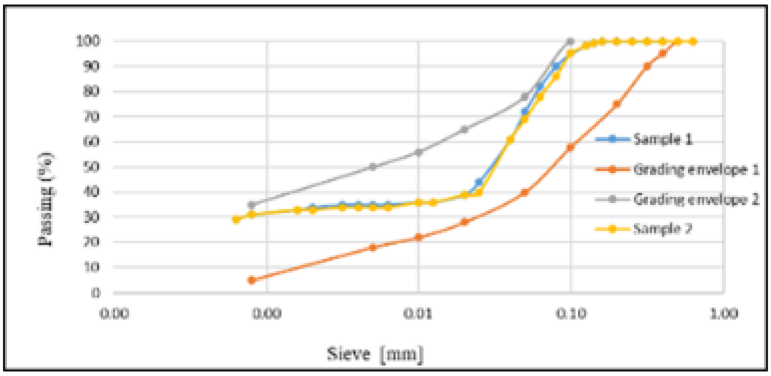

Figure 5 Grain-size distribution curves for the lateritic gravel from Avlamè and reference grain-size ranges

An analysis of Figure 5 shows that the grain-size distribution curves for both samples fall within the CEBTP [1] reference grain-size range, confirming that the material is lateritic gravel. This material is therefore suitable for use as a subbase layer in road construction. The key parameters from the particle size analysis results are presented in Table 1 below:

Table 1 Results of the sieve analysis of the lateritic gravel from Avlamè.

Description	D_{max} (mm)	C_{2mm} (%)	$C_{0,5mm}$ (%)	$C_{0,08mm}$ (%)
Sample 1	31.5	39	35	31
Sample 2	31.5	48	43	33
Average	31.5	43.5	39	32

The results of the particle size analysis in Table 1 show a maximum diameter (Dmax) of 31.5 mm for both samples. The percentage passing through the 2 mm sieve averages 43.5%, and the percentage passing through the 80 µm sieve is 32%. The specifications prescribed by the CEBTP [1] allowed for the following comparisons.

On the one hand, the percentage passing the 80 µm sieve (32%) is below the maximum threshold of 35% required for a sub-base course, which supports the material's use for this layer. On the other hand, this same percentage of fines exceeds the 20% limit required for a base course, which precludes its direct use as a base course without prior treatment.

These results are consistent with those reported in the literature for lateritic gravel in West Africa. Houanou et al. [6] obtained very similar results from the same quarry in Avlamè. Masamba et al. [25] report an 80 µm sieve retention of approximately 25% for lateritic gravel from Tambacounda (Senegal), and Issiakou et al. [26] note similar values for lateritic gravel from Dosso (Niger). Mbengue [27], in his study of lateritic subgrades from Saaba and Kamboinsé in Burkina Faso, reports percentages of material passing through an 80 µm sieve ranging from 29 to 33% for these sites—comparable to those obtained in the present study and all in compliance with CEBTP [1] requirements for the subbase layer. In contrast, the studies by Babaliyè et al. [5] on lateritic gravel from Djakotomey (Benin) found values exceeding 35%, with an average of 41.5% passing through an 80 µm sieve, which precludes its use in its natural state as either a foundation layer or a base layer.

3.1.2. Atterberg Limits

The results of the Atterberg limit tests on the lateritic gravel from Avlamè are summarized in Table 2 below:

Table 2 Results of the Atterberg limit tests on the lateritic gravel from Avlamè.

Description	W_l (%)	W_p (%)	I_p (%)
Sample 1	41	24	17
Sample 2	43	26	19
Average	42	25	18

The average plasticity index (PI) is 18%, with values ranging from 12 to 25%, which classifies the lateritic gravel from Avlamè as a moderately clayey soil according to the Guide to Road Earthworks (GTR) [28]. This index is acceptable for a subbase layer (PI ≤ 20% according to the CEBTP [1]; however, it exceeds the 15% threshold required for a base layer, indicating a significant sensitivity to water, which constitutes a limiting factor. These results are comparable to those of Houanou et al. [6], who obtained an IP of 17.67% at the same quarry, confirming the reproducibility of the measurements. Masamba et al. [25] report an IP of 11.60% for the gravel from Tambacounda (Senegal), indicating a lower clay content, while Babaliyè et al. [5] report an average IP of 23.3% for the gravel from Djakotomey (Benin), indicating higher plasticity. Similarly, Mbengue [27] obtained IP values ranging from 12 to 22.2% for the Saaba and Kamboinsé samples in Burkina Faso; the Avlamè gravel falls within the median range of these African values.

3.1.3. Methylene Blue Value (VBS)

The results of the methylene blue value test are presented in Table 3 below:

Table 3 Methylene Blue Value (VBS) of the lateritic gravel from Avlamè.

Description	Sample 1	Sample 2	Average
VBS (%)	0.20	0.22	0.21

The results for the methylene blue value average 0.21. This value falls within the range of 0.2 to 1.5, which classifies the Avlamè lateritic gravel as low in clay content and suitable for use as a subbase layer. This result is consistent with those reported by Dossou [29] and Houanou et al. [6] for the same quarry.

3.1.4. Organic Matter Content

The results of the organic matter content test for the Avlamè lateritic gravel are presented in Table 4 as follows:

Table 4 Organic matter content of the Avlamè lateritic gravel.

Description	Sample 1	Sample 2	Average
Organic Matter Content (%)	0.26	0.20	0.23

The average organic matter content is 0.23%, a value well below the 1.5% threshold set by the CEBTP [1]. This result confirms that the material has a low organic content and is unlikely to undergo chemical reactions.

3.1.5. Modified Proctor Test

The results of the modified Proctor test are presented as a curve with moisture content on the x-axis and dry density on the y-axis (see Figure 6).

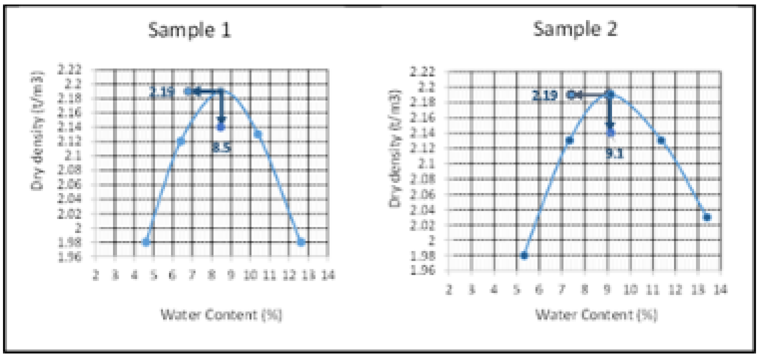

Figure 6 Proctor curve for raw lateritic gravel

Based on the Proctor curves for the two samples shown in Figure 6, the results for the Proctor compaction parameters are summarized in Table 5 below:

Table 5 Modified Proctor parameters for Avlamè lateritic gravel.

Parameter	Sample 1	Sample 2	Average
γd max (t/m^3)	2.19	2.19	2.19
ω_{OPM} (%)	8.5	9.1	8.8

Table 5 shows that the maximum dry density of the Avlamè lateritic gravel, determined using the Modified Optimum Proctor test, is 2.19 t/m^3. The specifications for using lateritic gravel as a base course for pavements require a minimum dry density of at least 2 t/m^3 and a moisture content between 7% and 13%. When used as a subbase layer, lateritic gravel must have a minimum dry density of 1.8 to 2 t/m^3 and a moisture content between 7% and 13%. These dry density limits are lower than those of our sample, and the moisture content falls within the required range. The material is therefore suitable for use as both a foundation layer and a base layer.

These results are similar to those obtained by Ahouet and Elenga [30] (γdmax = 2.15 t/m^3) and by Houanou et al. [6] (γdmax = 2.17 t/m^3) for lateritic gravel. However, they are higher than those reported by Masamba et al. [25] and Babaliyè [31], who found densities on the order of 2.0 ± 0.1 t/m^3. Mbengue [27] obtained γdmax values ranging from 2.02 to 2.06 t/m^3 for lateritic materials from Saaba (Burkina Faso), which are lower than those from Avlamè. This study shows that the results obtained for the lateritic gravel from Avlamè are consistent with the values reported for lateritic materials in West Africa.

3.1.6. CBR index of lateritic gravel

The results of the CBR test on samples of lateritic gravel from Avlamè show the puncture measurements taken on test specimens divided into three (3) series according to the molds, as well as the values for the linear swelling of the test specimens. These results are recorded in Table 6 below:

Table 6 Results of the CBR test on Avlamè lateritic gravel after 4 days of water saturation.

Description	Sample 1	Sample 2	Average
CBR at 100% OPM (%)	77	39	58
CBR at 95% OPM (%)	36	32	34
CBR at 90% OPM (%)	18	16	17
Linear Swelling (%) à 95% OPM	0.04	0.04	0.04

The CBR index of raw lateritic gravel, determined after four days of soaking at 95% of the Optimum Proctor Moisture content (OPM), averages 34%, with a relative linear swelling of 0.04%. These results are lower than those obtained by Dossou [29] and Houanou et al. [6] in their studies of the Avlamè quarry.

The CEBTP recommendations [1] state: "Regardless of the structure in which they are used, base course materials must have a CBR of at least 30, determined at a dry density corresponding to 95% of the OPM. However, a value of 25 is acceptable for traffic classes T1 and T2, and 35 for traffic classes T4 and T5." These recommendations are verified for the CBR value after 96 hours of water absorption (34%) for traffic classes T1 and T2 but are not recommended for traffic classes T4 and T5. The material is therefore suitable for use as a subbase layer in pavements for traffic classes T1 and T2.

Regarding the base course: "The CBR bearing index shall be at least 80 for a density corresponding to 95% of the OPM. If the material does not achieve this bearing capacity, it must be improved or treated. A CBR index of 60 may be accepted for T1 traffic." In this study, the CBR value at 95% of the OPM for the Avlamè gravel is 34%, which is lower than the minimum value of 80 required by the CEBTP [1]; therefore, this material cannot be used as a base course, not even for low-traffic pavements. The material therefore requires improvement for use as a base course.

These conclusions are similar to those obtained by Mbengue [27], who shows that lateritic gravel can be used as a subbase but not as a base course without prior treatment.

3.2. Influence of Jute Fiber Length on the CBR Index

An initial series of tests was conducted while keeping the fiber content constant at 1% by mass, for lengths of 0, 1, 2, and 3 cm. The results are summarized in Table 7 as follows:

Table 7 Effect of jute fiber length (fiber content fixed at 1% by mass) on the CBR index at 95% of the OPM.

Fiber length	CBR Sample 1 (%)	CBR Sample 2 (%)	CBR Sample (%)
0 cm (Raw gravel)	36	32	34.0
1 cm	52	46	49.0
2 cm	46.0	41	43.5
3 cm	40	34	37.0

Table 7 allowed us to plot a histogram showing the variation in the CBR index as a function of fiber length. This variation is illustrated in Figure 7, which is shown below:

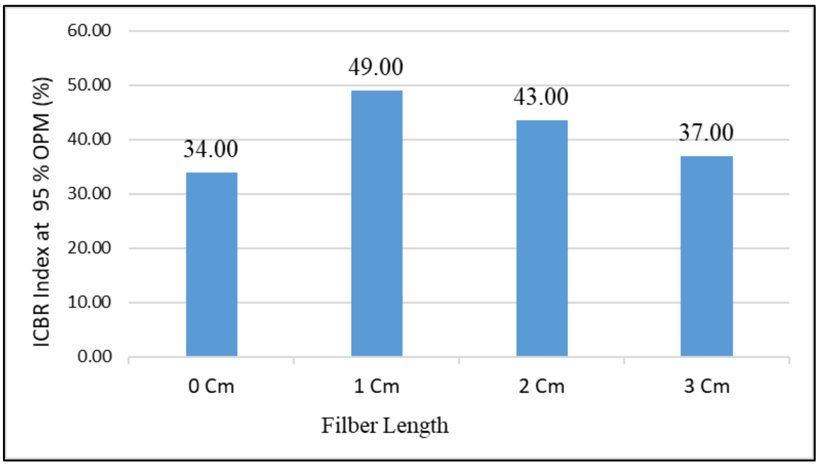

Figure 7 Variation in the CBR index (95% OPM) as a function of jute fiber length, for a constant dosage of 1%.

The results in Table 7 and Figure 7 show a significant improvement in the CBR index after the addition of jute fibers. Analysis of this figure shows that a fiber length of 1 cm appears to be the optimal length in this study, as it yields the highest CBR value 49% compared to 34% for the material without fibers, 43.5% for 2 cm, and 37% for 3 cm. This represents a 44.1% improvement over the untreated gravel. This improvement is attributed to better distribution of the fibers within the clay matrix and more effective interaction between the fibers and the soil at this length, whereas longer fibers tend to become entangled or reduce the homogeneity of the mixture.

This decline in performance as fiber length increases is attributed to two complementary phenomena: (i) excessive entanglement of long fibers, which hinders their homogeneous distribution within the granular matrix [12]; (ii) a reduction in fiber-soil contact density, linked to a decrease in the number of fibers per unit volume for a given mass incorporated, which reduces the efficiency of load transfer [11].

These observations are consistent with other studies. Brahmachary and Rokonuzzaman [16] demonstrated, using bamboo fibers incorporated into ordinary soil, that short fibers provide better mechanical anchorage and a more uniform distribution. Aggarwal and Sharma [32] showed that the maximum CBR value is obtained with 10-mm jute fibers at a dosage of 0.8%, reaching 2.5 times that of unreinforced soil. In other words, the 10-mm short fibers yield the best results among the lengths tested (5 to 20 mm). The study by Ramkrishnan et al. [33] showed that jute fibers 1.0 cm in length provide higher penetration resistance than fibers 0.5 cm and 1.5 cm in length, at the optimal fiber content. It demonstrated that the 1 cm length (optimum) led to an increase in the CBR value as the fiber content increased. Mozu-Simpson et al. [13] confirm this result in a similar context (fibers from palm fruit stalks).

These consistent findings in the literature reinforce the robustness of the result obtained. The 1-cm length is therefore selected as the optimal length for the remainder of the study.

3.3. Effect of Fiber Content on the CBR Index (1 cm Fibers)

A second series of tests was conducted using 1-cm-long fibers, varying the dosage from 0 to 1.25% by mass. The results are presented in Table 8.

Table 8 Effect of the dosage of 1-cm jute fibers on the CBR index at 95% of the OPM.

Fiber Content (%)	CBR Sample 1 (%)	CBR Sample 2 (%)	Average CBR (%)
0.25	43	39	41.0
0.50	62	56	59.0
0.75	72	67	69.5
1.00	52	46	49.0
1.25	46	41	43.5

Table 8 allows us to plot a histogram showing the effect of jute fiber content on the CBR index at 95% OPM. Figure 8 below shows the variation in the CBR index (95% OPM) as a function of the content of 1cm long jute fibers.

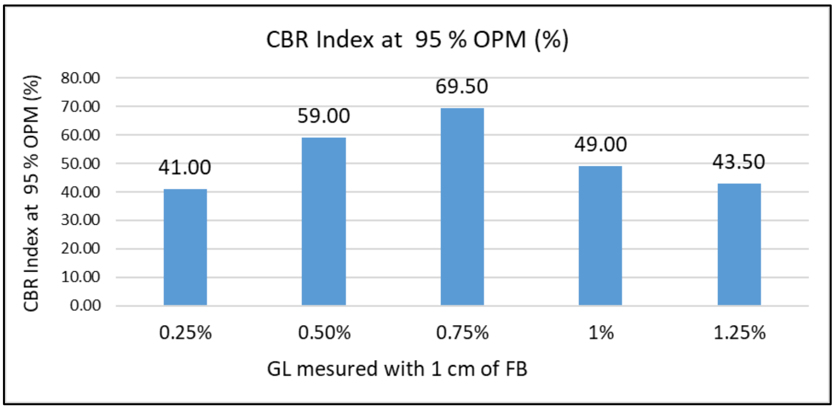

Figure 8 Variation in the CBR index (95% OPM) as a function of the content of 1-cm-long jute fibers.

Analysis of Table 8 and Figure 8 shows a nonlinear trend in the CBR index as a function of fiber content. The CBR index increases gradually from a fiber content of 0.25% (CBR = 41.0%) until it reaches a maximum of 69.5% at an optimal fiber content of 0.75%. Beyond this threshold, a decrease is observed: the CBR drops to 49.0% at 1.00% fiber content and to 43.5% at 1.25%. This behavior is characteristic of saturation of the fiber network within the granular matrix, leading to a loss of mixture homogeneity and a reduction in fiber-soil interactions [11].

The improvement in the CBR from 34% (unamended soil) to 69.5% (optimal composite) represents an increase of 104.4%. This result is consistent with the work of Kumar et al. [11], who achieved a 226.92% improvement in an expansive soil with an optimal jute fiber content of 1.25%. Wang et al. [12] confirm a gradual increase in strength up to a threshold fiber content, followed by a decline, in an expansive soil treated with jute fibers. Tanko et al. [10] demonstrated that the maximum CBR value and the maximum unconfined compressive strength of 494 kN/m^2 for a lateritic soil were achieved with a sisal fiber content of 0.75%. Singh and Jamatia [34] demonstrated that the optimal percentage yielding the maximum CBR and maximum compressive strength is 0.75% jute fibers. These data confirm the robustness of the results obtained in this study. The value of 0.75% is therefore selected as the optimal dosage for the composite material formulation.

From a regulatory standpoint, the CBR of 69.5% achieved for the optimal composite (aggregate + 0.75% 1-cm jute fibers) is promising: it exceeds the 60% threshold accepted by the CEBTP [1] for use as a base course for T1 and T2 traffic classes, while remaining below the general 80% threshold required for higher traffic classes. This result should be viewed in the context of the work by Tankpinou et al. [3] on silty sand from Tohouè (Benin), in which lithostabilization with crushed granite achieved a CBR of 70% at a dosage of 40% crushed granite, a value comparable to that obtained here with only 0.75% fibers, highlighting the remarkable effectiveness of fiber reinforcement at very low dosages. The 0.75% dosage is therefore selected as the optimal formulation, offering the additional advantage of being economically accessible and environmentally friendly, as the fibers are sourced from jute bags that are abundant in local markets in Benin.

4. Conclusion

This study focused on the formulation of a composite material based on lateritic gravel from Avlamè (Benin) reinforced with jute fibers, with a view to its application in road construction for the base layers of flexible pavements. The experimental approach was conducted in two successive stages: optimization of fiber length, followed by optimization of the dosage at the optimal length.

The main conclusions of this study are as follows:

- Avlamè lateritic gravel in its raw state has a CBR of 34% to 95% of the OPM. It can be used as a subbase layer for traffic classes T1 to T2, but requires treatment for use as a base layer.
- The incorporation of jute fibers significantly improves the CBR value. The optimal fiber length is 1 cm: at a constant dosage of 1% by mass, the CBR reaches 49.0%, compared to 43.5% for 2-cm fibers and 37.0% for 3-cm fibers.
- For 1-cm fibers, optimizing the dosage yields a CBR of 69.5% at an incorporation rate of 0.75% by mass, representing a 104.4% improvement over untreated gravel.
- The optimal formulation selected is: lateritic gravel reinforced with 1-cm jute fibers at a dosage of 0.75% by mass (CBR = 69.5%). This composite meets the CEBTP (1984) requirements for use as a subbase and base course for T1 and T2 traffic classes.

These results confirm the potential of jute fibers as a reinforcing agent for lateritic materials with low bearing capacity, offering both a technical and environmental alternative to conventional stabilizers such as cement or granite crushed stone.

Further studies are recommended to: evaluate the long-term behavior of the composite material under actual traffic conditions; study the alkalinity of the mixture; and analyze its behavior under the alternating wet-dry cycles characteristic of Benin's tropical climate.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that they have no conflicts of interest.

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