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Improvement of Mechanical Qualities of Clay Material through Coconut Fiber Stabilization

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Abstract

The criticisms regularly formulated towards clay or soil, in general, are its weak mechanical qualities and low water quality. Therefore, it is necessary to find techniques to improve the properties of this material, which is widely used worldwide. Here, we propose stabilizing clay with coconut fiber as a solution to enhance its mechanical properties. To do this, we used an experimental method, first determining the geotechnical properties of the clay and then its mechanical properties. The geotechnical study using the Proctor Test revealed that the dry density of the clay is γ_b = 1.42 g/cm^3, and its water content is W = 22.3%. By applying the rolling method, the Atterberg limits were determined: liquid limit W_l = 63.6, plastic limit Wp = 27.9, plasticity index Ip = 35.7, and consistency index Ic = 1.46. With $25 < I_P = 35.7 < 40$, the material falls into class A3, a marly clay. Additionally, Ic = 1.45 > 1.3, according to the water classification, it falls into class A3ts. The mechanical part focused on compression and flexural strengths obtained using a PROETI hydraulic press. We obtained a flexural strength of 0.63 MPa for simple clay (BA); 0.89 MPa for clay + 0.25% fiber (BAF1/4); 1.68 MPa for clay + 0.5% fiber (BAF1/2); 1.87 MPa for clay + 0.75% fiber (BAF3/4); and 3.91 MPa for clay + 1% fiber (BAF1). As for the compression strength, BA = 5.90 MPa, BAF1/4 = 6.395 MPa, BAF1/2 = 6.292 MPa, BAF3/4 = 6.065 MPa, and BAF1 = 5.423 MPa. The addition of fiber has thus improved the mechanical qualities of the simple clay. These stabilized bricks can be used for sustainable and bioclimatic construction, providing higher durability and good comfort.

Keywords

Compression Strength, Flexural Strength,Coconut Fiber, Clay, Geotechnical

Properties

1. Introduction

A. Research Context. Clayey soils represent one of the most abundant natural resources [1] [2] and are frequently utilized in various construction and engineering projects. However, despite their availability, these soils often exhibit mechanical properties that restrict [3] their use in applications requiring high strength [4]. Improving these properties constitutes a major challenge in the fields of geotechnics [5] and construction [6].

B. Justification of the Study. Soil stabilization using plant fibers such as jute, palm fiber, sisal fiber, bamboo fiber, flax fiber, kapok fiber, etc., has emerged as a promising method for enhancing the mechanical characteristics of clayey soils. Among the available fibers, coconut fiber stands out for its favorable mechanical properties and natural durability. Nevertheless, despite promising studies on this subject, a deeper understanding of the effects of coconut fiber stabilization on the mechanical qualities of clay remains necessary.

C. Research Objectives. This study aims to thoroughly investigate the impact of coconut fiber stabilization on the mechanical properties of clay. Specific objectives include evaluating the compression and flexural strength of stabilized samples, as well as analyzing geotechnical properties such as liquid limit, plastic limit, plasticity index, and consistency index. Furthermore, this research aspires to provide practical recommendations for the implementation of this innovative technique in construction and engineering projects.

2. Brief Literature Review

2.1. Mechanical Properties of Unstabilized Clay

Clayey soils are widely distributed in various regions around the world, characterized by their fine composition [7] and high plasticity [8]. While these soils offer an abundance of cost-effective construction materials [9] their intrinsic mechanical properties can be limiting [6]. Indeed, unstabilized clay often exhibits low compressive strength [10] and bearing capacity, which can hinder their use in construction projects requiring strong and durable foundations.

2.2. Use of Plant Fibers in Soil Stabilization

The integration of plant fibers in soil stabilization has emerged as an innovative method addressed by several authors [11]-[16] to enhance the mechanical characteristics of clayey soils. Plant fibers such as jute fiber [17] [18], palm fiber [19] [20], sisal fiber [21] [22], bamboo fiber [23], flax fiber, and kapok fiber, due to their fibrous nature and strength, can act as natural reinforcements, strengthening the soil matrix and thereby improving its mechanical properties. This approach has the additional advantage of being cost-effective and environmentally friendly [24] [25].

2.3. Previous Studies on Coconut Fiber Stabilization

Several previous studies [26] [27] [28] have already explored the use of coconut fiber as a stabilizing agent for soils. In addition to its abundant availability - the world produces at least 30 million tons of coconuts [29], coconut fiber possesses specific advantages such as its tensile strength [26] [27] [30] and natural durability. These studies have shown promising results, suggesting that the incorporation of coconut fiber can significantly enhance the mechanical properties of clayey soils. However, there are specific aspects that need further clarification and in-depth exploration for a broader and more effective application of this method.

Previous studies demonstrate a high potential for this approach, underscoring the importance of continuing research in this field.

3. Materials and Methods

The clayey materials are obtained by excavating to a depth of 30 cm using manual picks and shovels. The extraction site and the extracted sample are shown in **Figure 1**.

Figure 1. Clay Extraction Site (a) Extracted Sample (b).

3.1. Geotechnical Tests

These involve determining the Atterberg limits, water content, and dry density using the Proctor Test. The Atterberg limits are conventional geotechnical characteristics of soil that delineate the thresholds between:

- Transition from liquid state to plastic state: liquid limit (L_l),
- Transition from plastic state to solid state: plastic limit (L_p).

This determination of Atterberg limits was carried out in accordance with the NF P 94-051 standard [31] and is illustrated in **Figure 2**. This allows us to deduce the plasticity index I_p:

$$I_p = L_l - L_p \tag{1}$$

and the compactness index I_c:

$$I_c = \frac{(L_l - W_e)}{I_p} \tag{2}$$

where W_e is the water content of the clay, previously determined using the Proctor test.

The Proctor Test itself was conducted in accordance with the NF P94-093 standard [32].

Figure 2. Procedure for Determining Limits: (a) Sampling, (b) Settling, (c) Kneading of the Passing, (d) Sampling of the Kneaded, (e) Weighing, and (f) Recorded Tare.

3.2. Mechanical Tests

3.2.1. Sample Preparation

Adobe bricks of each composition in **Table 1** were manually crafted, as shown in **Figure 3**, using a metal mold with dimensions: 4 × 4 × 16 cm^3. They were air-dried in natural convection for 12 days. The average masses of the different compounds were recorded every day during the drying process to monitor their progress. The results of these measurements are documented in **Table 2**. It can be observed that the bricks were already dry between the 8th and 9th day as their masses remained constant from these days onward.

Figure 3. Sample preparation process for tests.

Table 1. Mix composition.

Type of bricks	Notation	Fiber rate	Water
Simple clay	BA	-	25%
Clay -fibers	BAF	Fibres 0, 25%	30%
		Fibres 0, 5%	34%
		Fibres 0, 75%	37%
		Fibres 1%	40%

Table 2. Weights of the bricks per weighing day.

Days		1	2	3	4	5	6	7	8	9	10	11	12
Mass of bricks (g)	**BA**	414	371	368	365	363	361	361	360.5	360.5	360	360	360
	BAF1/4	423	369	358	355	352	352	351	351.5	350	350	350	350
	BAF1/2	435	389	364	360.5	355	351	348	348.6	348	348	348	348
	BAF3/4	443	394	374	365	358	350	347.4	347	347	347	347	347
	BAF1	456	397	363	357	350.6	348.3	346.2	346	346	346	346	346

3.2.2. Conducting Compression and Flexural Tests

The mechanical properties, including flexural strength and compressive strength, were determined at the Eco Materials Laboratory of the International Institute for Water and Environmental Engineering (2ie) using a Controlab hydraulic press, as shown in **Figure 4**, with a maximum applied load capacity of 300 kN. The breaking force is the maximum force that led to the sample's fracture or breakage. From this maximum force, the rupture pressure is deduced, referred to as either compressive strength or flexural strength, depending on the case. For this study, three-point bending was employed, as shown in **Figure 4(a)**. The two roller supports, each with a diameter of 10 mm, are spaced at a distance of L = 106.7 mm. The pressure force is applied through the third roller at the midpoint between them.

$$\sigma_f = \frac{3FL}{2b^3} \tag{3}$$

where b (mm) is the edge of the square section of the prism, and F (N) is the breaking force.

As for compressive strength, it is determined using the relation:

$$\sigma_c = \frac{F}{S} \tag{4}$$

where σ_c is the compressive strength of the specimen in MPa, F is the maximum load sustained by the specimen in N, and S is the average value of the cross-sectional area in mm^2.

The force F is applied to the sample until it is crushed **Figure 4(b)**.

The press is connected to a computer, allowing real-time monitoring of the pressure force applied to the brick **Figure 4(c)**.

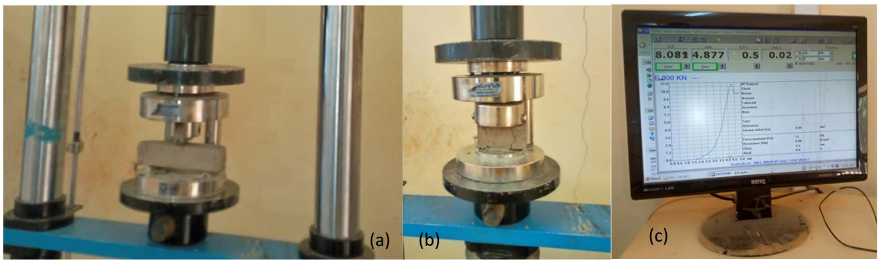

Figure 4. Conducting mechanical tests. (a) Flexion, (b) Compression, (c) Recording computer.

4. Results and Discussions

4.1. Geotechnical Properties

4.1.1. Proctor Tests

For the pure clay, we obtained an optimal water content (W_e) de 22.3% at a dry density γ_b = 1.42 g/cm^3. For different proportions of coconut fiber (0.25%; 0.50% and 0.75%), we obtained the pairs: (W_e; γ_b) as follows (W_e = 28.2%; γ_b = 1.47 g/cm^3); (W_e = 24.9%; γ_b = 1.48 g/cm^3); (W_e = 24.2%; γ_b = 1.53 g/cm^3). It is observed that the water content decreases with the fiber content, while the dry density increases. The decrease in W_e indicates that after mixing, the fibers absorb a portion of the added water, explaining the regression of water content with increasing fiber content in the mixtures. The increase in dry density reflects high compaction of the clay-fiber composite, indicating strong internal cohesion after compaction.

4.1.2. Atterberg Limits

Liquid limit L_l = 63.6, plastic limit L_p = 27.9, plasticity index I_p = 35.7, consistency index I_c = 1.456. Based on this, the clay is classified as follows: 25 < I_p = 35.7 < 40, making it a marly clay of class A3. According to the Road Earthwork Guide (GTR) [33], if this clay is to be used in an earthwork project, lime treatment is required for soils of types A3 and A4, which means soils with a significant liquid limit and a plasticity index greater than 20. Additionally, I_c= 1.456 >1.3, according to the hydric classification, placing it in class A3ts.

With a plasticity of I_p = 35.7 > I_p = 14% recommended by [34], it is suitable for making compressed earth blocks (CEBs).

4.2. Mechanical Properties

4.2.1. Flexural Strength

The evolution of the pressure force applied to the samples of different compositions is shown in **Figure 5** for the pure clay (BA) and in **Figure 6** for the clay-fiber compositions. The terms E_1, E_2 and E_3 respectively denote sample number 1, number 2, and number 3. For BA, the breaking forces are 136.21 N and 200.46 N for E_1 and E_2 respectively. In contrast, samples composed of clays stabilized with fiber proportions of 0.25%, 0.50%, 0.75%, and 1% exhibit greater breaking forces. The stabilized bricks with 0.25% fibers have a breaking force ranging from 240 N to 250 N, and those stabilized with 0.5% fibers between 440 N and 460 N. The Clay-Fiber Bricks of 0.75% have a breaking force of 500 N; Stabilizations with 1% fibers have a range of 960N to 1100N. In some cases, the test did not lead to a clear rupture. These cases are considered aberrations and are not taken into account. Thus, using **Equation 3**, we deduce flexural strengths of 0.63 MPa for pure clay (BA); 0.89 MPa for clay + 0.25% fiber (BAF1/4); 1.68 MPa for clay + 0.5% fiber (BAF1/2); 1.87 MPa for clay + 0.75% fiber (BAF3/4); 3.91 MPa for clay + 1% fiber (BAF1), which is slightly better than that found by [35] who used lime-fiber mixture as stabilizers. Flexural strength increases with fiber content, indicating that coconut fibers enhance the flexibility of the bricks by reinforcing the bonds between the solid clay particles.

- Simple Clay Bricks (BA)

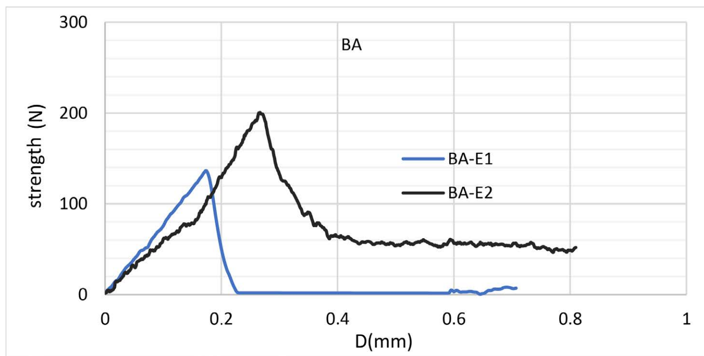

Figure 5. Flexural force of the Simple Clay Brick (BA).

- Bricks of clay added fiber for: 0.25%; 0.5%; 0.75% and 1%

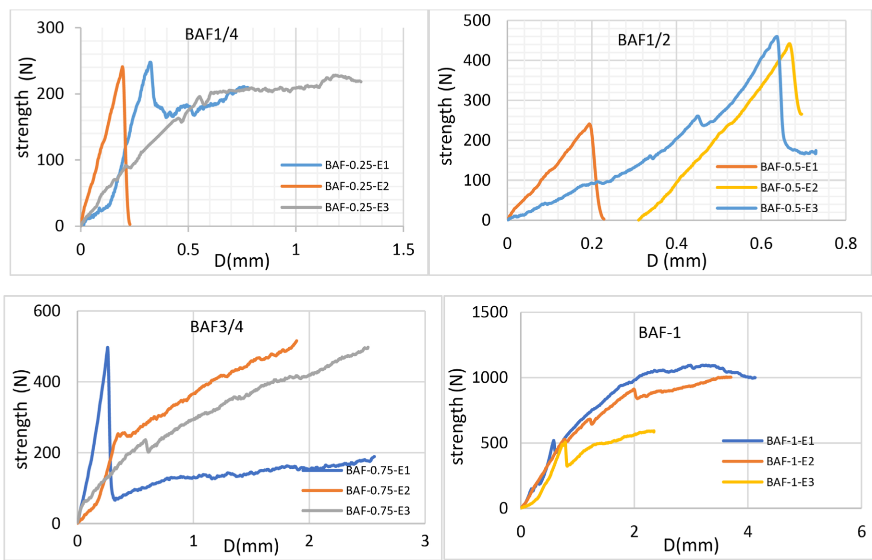

Figure 6. Variation in flexural rupture force for different clay-fiber brick composites.

4.2.2. Compressive Strength

The behaviors of the bricks under the effect of compressive load are illustrated in

Figure 7 for BA and **Figure 8** for the different clay-fiber compositions at 0.25%, 0.5%, 0.75%, and 1%. By applying **Equation (4)**, we obtain the values of the compressive stress σ_c (MPa). Thus, we have: compression strength for BA = 5.90 MPa, BAF1/4 = 6.395 MPa, BAF1/2 = 6.292 MPa, BAF3/4 = 6.065 MPa, and BAF1 = 5.423 MPa. It is noted that the compressive strength σ_c increases with the increase in fiber content up to 0.5% of it. Beyond that, at 0.75% and 1% fiber content, the compressive stress σ_c decreases. This means that when the fiber content is high, it makes the compound more ductile, leading to a decrease in σ_c. Therefore, it can be deduced that there is an optimal amount of fiber for good compressive strength. On the other hand, the presence of fiber results in a reduction in crack propagation under tension after initial deformation, a decrease in the number of cracks caused by shrinkage, and a decrease in the hydraulic conductivity of compacted clayey soils [36] [37].

- Simple Clay bricks (BA)

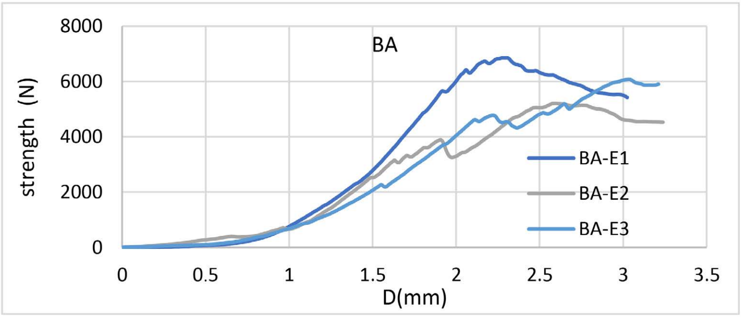

Figure 7. Variation in the compressive force for plain clay bricks (BA).

- Bricks of clay added fiber for: 0.25%; 0.5%; 0.75% and 1%

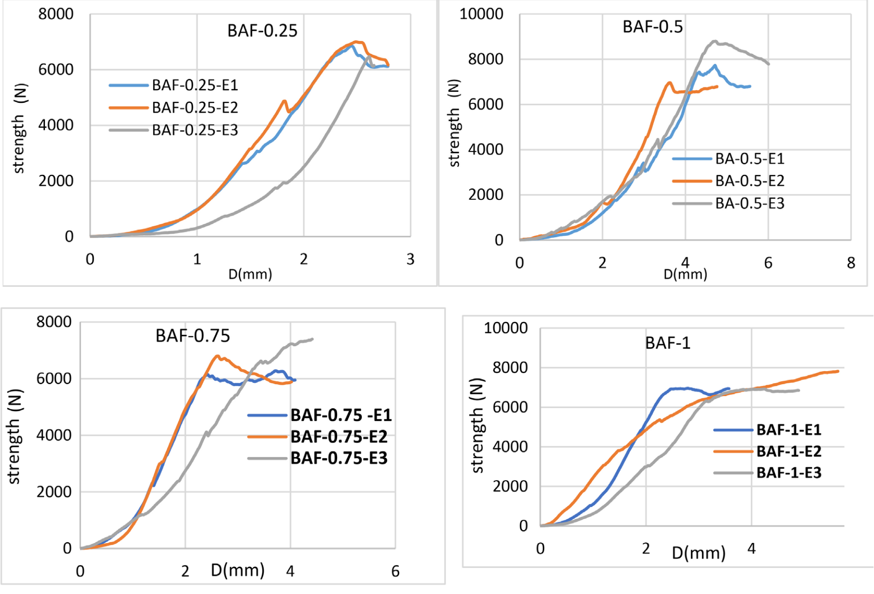

Figure 8. Variation in the compressive force of different clay-fiber brick compositions.

5. Conclusions

At the end of this study on the improvement of the mechanical qualities of clayey material through coconut fiber stabilization, several results have been highlighted:

- The class of the clay used in this study is Class A3, a marly clay because 25 < PI = 35.7 < 40;
- This clay can be used for earthwork, provided it is stabilized with lime. It is also suitable for making compressed earth bricks for the construction of bioclimatic dwellings;
- This clay is of A3ts hydraulic class because its compactness index $I_c = 1.45 > 1.3$;
- Flexural strength increases with the increase in the fiber content in the compound, ranging from 0.63 MPa for simple clay (BA) to 3.91 MPa for clay + 1% fiber (BAF1);
- Compression strength initially increases when adding 1/4 of the fiber, going from 5.90 MPa for BA to 6.395 MPa for BAF1/4. Beyond this point, compression strength decreases.

The addition of coconut fiber improves the mechanical properties of the clay. However, there is an optimal fiber ratio that should not be exceeded for compression strength. In terms of future perspectives, it would be important to combine coconut fiber with other bio-stabilizers and explore improvements in mechanical, thermal, and especially durability aspects. Bi-stabilization or tri-stabilization could be considered.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Meunier, A. (2008) Annuaire des minéraux du canada, Argiles. http://books.google.fr/books?id=vQvAAAAACAA

[2] Moronta, A. (2004) Catalytic and Adsorption Properties of Modified Clay Surfaces. *Interface Science and Technology*, **1**, 321-344. https://doi.org/10.1016/s1573-4285(04)80046-2

[3] Majid, A.E., Baba, K. and Razzouk, Y. (2023) Assessing the Impact of Plant Fibers on Swelling Parameters of Two Varieties of Expansive Soil. *Case Studies in Chemical and Environmental Engineering*, **8**, Article ID: 100408. https://doi.org/10.1016/j.cscee.2023.100408

[4] Bo, M.W., Arulrajah, A., Sukmak, P. and Horpibulsuk, S. (2015) Mineralogy and Geotechnical Properties of Singapore Marine Clay at Changi. *Soils and Founda-*

tions, **55**, 600-613. https://doi.org/10.1016/j.sandf.2015.04.011

[5] Proust, C., Jullien, A. and Le Forestier, L. (2004) Détermination indirecte des limites d'Atterberg par gravimétrie dynamique. *Comptes Rendus*. *Géoscience*, **336**, 1233-1238. https://doi.org/10.1016/j.crte.2004.06.003

[6] Galvín, A.P., López-Uceda, A., Cabrera, M., Rosales, J. and Ayuso, J. (2020) Stabilization of Expansive Soils with Biomass Bottom Ashes for an Eco-Efficient Construction. *Environmental Science and Pollution Research*, **28**, 24441-24454. https://doi.org/10.1007/s11356-020-08768-3

[7] Malatrait, A.M. (1980) Inventaire des ressources en matériaux argileux de la région de Rhome-Aples. 1981st Edition, No. 7. Lion.

[8] Ural, Z. and Ural, N. (2018) The Importance of Clay in Geotechnical Engineering. In: Editor, *Built by Scientists*, *for Scientists*, publisher, 83-101.

[9] Sujatha, E.R. and Selsia Devi, S. (2018) Reinforced Soil Blocks: Viable Option for Low Cost Building Units. *Construction and Building Materials*, **189**, 1124-1133. https://doi.org/10.1016/j.conbuildmat.2018.09.077

[10] Mendoza, R. (2021) Shear Strength and Elastic Modulus Behavior of Coconut Fiber-Reinforced Expansive Soil. *IOP Conference Series*: *Materials Science and Engineering*, **1144**, Article ID: 012043.

[11] Huyen, B.T., Nguyen, D.H. and Sebaibi, N. (2018) A Simple Review of Using Coconut Fiber as Reinforcement in Composite. *The* 8*th International Conference of Asian Concrete Federation*, Fuzhou, 4-7 November 2018, 307-319.

[12] Estabragh, A.R., Bordbar, A.T. and Javadi, A.A. (2012) A Study on the Mechanical Behavior of a Fiber-Clay Composite with Natural Fiber. *Geotechnical and Geological Engineering*, **31**, 501-510. https://doi.org/10.1007/s10706-012-9602-6

[13] Bui, H., Sebaibi, N., Boutouil, M. and Levacher, D. (2020) Determination and Review of Physical and Mechanical Properties of Raw and Treated Coconut Fibers for Their Recycling in Construction Materials. *Fibers*, **8**, Article No. 37. https://doi.org/10.3390/fib8060037

[14] Attom, M.F., Al-Akhras, N.M. and Malkawi, A.I.H. (2009) Effect of Fibres on the Mechanical Properties of Clayey Soil. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, **162**, 277-282. https://doi.org/10.1680/geng.2009.162.5.277

[15] Obsharova, A.V. and Grishina, A.S. (2021) Effect of the Fiber Reinforcement on the Mechanical Properties of Clay Soils, Including Properties under Conditions of Seasonal Freezing and Thawing. *Journal of Physics*: *Conference Series*, **1928**, Article ID: 012067. https://doi.org/10.1088/1742-6596/1928/1/012067

[16] Regina, C., Baldin, B., Maiky, K.Y. and Gustavo, W. (2023) Mechanical Properties of a Clay Soil Reinforced with Rice Husk under Drained and Undrained Conditions. *Journal of Rock Mechanics and Geotechnical Engineering*, **15**, 2676-2686.

[17] Lal, D., Reddy, P., Kumar, R.S. and Rao, V.G. (2020) Stabilization of Expansive Soil by Using Jute Fiber. *IOP Conference Series*: *Materials Science and Engineering*, **998**, Article ID: 012045. https://doi.org/10.1088/1757-899x/998/1/012045

[18] Carmel, V.A. and Vinu, T. (2015) Stabilization of Soft Clay Using Lime and Jute Fibres. *International Journal of Engineering Research and Technology*, **3**, 1-5.

[19] Qu, J. and Zhu, H. (2021) Function of Palm Fiber in Stabilization of Alluvial Clayey Soil in Yangtze River Estuary. *Journal of Renewable Materials*, **9**, 767-787. https://doi.org/10.32604/jrm.2021.013816

[20] Chompoorat, T., Likitlersuang, S., Buathong, P., Jongpradist, P. and Jamsawang, P.

(2023) Flexural Performance and Microstructural Characterization of Cement-Treated Sand Reinforced with Palm Fiber. *Journal of Materials Research and Technology*, **25**, 1570-1584. https://doi.org/10.1016/j.jmrt.2023.06.036

[21] Thennarasan Latha, A., Murugesan, B. and Skariah Thomas, B. (2023) Compressed Earth Block Reinforced with Sisal Fiber and Stabilized with Cement: Manual Compaction Procedure and Influence of Addition on Mechanical Properties. *Materials Today*: *Proceedings*. https://doi.org/10.1016/j.matpr.2023.04.373

[22] Wu, Y., Li, Y. and Niu, B. (2014) Assessment of the Mechanical Properties of Sisal Fiber-Reinforced Silty Clay Using Triaxial Shear Tests. *The Scientific World Journal*, **2014**, Article ID: 436231. https://doi.org/10.1155/2014/436231

[23] Tong, F., Ma, Q. and Xing, W. (2019) Improvement of Clayey Soils by Combined Bamboo Strip and Flax Fiber Reinforcement. *Advances in Civil Engineering*, **2019**, Article ID: 7274161. https://doi.org/10.1155/2019/7274161

[24] Anglade, E., Aubert, J., Sellier, A. and Papon, A. (2022) Physical and Mechanical Properties of Clay-Sand Mixes to Assess the Performance of Earth Construction Materials. *Journal of Building Engineering*, **51**, Article ID: 104229. https://doi.org/10.1016/j.jobe.2022.104229

[25] Khorram, N. and Rajabi, A.M. (2022) Strength Properties and Microstructural Characteristics of Clay Treated with Alkali Activated Mortar and Fiber. *Construction and Building Materials*, **341**, Article ID: 127486. https://doi.org/10.1016/j.conbuildmat.2022.127486

[26] Widianti, A., Diana, W. and Fikriyah, Z.S. (2021). Unconfined Compressive Strength of Clay Strengthened by Coconut Fiber Waste. *Proceedings of the* 4*th International Conference on Sustainable Innovation* 2020-*Technology*, *Engineering and Agriculture* (*ICoSITEA* 2020), **199**, 47-50. https://doi.org/10.2991/aer.k.210204.010

[27] Sun, Z., Zhang, L., Liang, D., Xiao, W. and Lin, J. (2017) Mechanical and Thermal Properties of PLA Biocomposites Reinforced by Coir Fibers. *International Journal of Polymer Science*, **2017**, Article ID: 2178329. https://doi.org/10.1155/2017/2178329

[28] Kaushik, D. and Singh, S.K. (2021) Use of Coir Fiber and Analysis of Geotechnical Properties of Soil. *Materials Today*: *Proceedings*, **47**, 4418-4422. https://doi.org/10.1016/j.matpr.2021.05.255

[29] Gaspar, F., Bakatovich, A., Davydenko, N. and Joshi, A. (2020) Building Insulation Materials Based on Agricultural Wastes. In: Pacheco-Torgal, F., Ivanov, V. and Tsang, D.C.W., Eds., *Bio-Based Materials and Biotechnologies for Eco-Efficient Construction*, Elsevier, 149-170. https://doi.org/10.1016/b978-0-12-819481-2.00008-8

[30] Tamassoki, S., Daud, N.N.N., Jakarni, F.M., Kusin, F.M., Rashid, A.S.A. and Roshan, M.J. (2022) Compressive and Shear Strengths of Coir Fibre Reinforced Activated Carbon Stabilised Lateritic Soil. *Sustainability*, **14**, Article No. 9100. https://doi.org/10.3390/su14159100

[31] de Normalisation, A.F. (1993) Norme française NF P 94-051: Détermination des limites d'Atterberg.

[32] AFNOR (2014) NF P94-093 Standard. 1-30.

[33] LCPC (2000) Réalisation des remblais et des couches de forme. 2ème Edition.

[34] Laibi, A.B., Gomina, M., Sorgho, B., Sagbo, E., Blanchart, P., Boutouil, M., *et al*. (2017) Caractérisation physico-chimique et géotechnique de deux sites argileux du Bénin en vue de leur valorisation dans l'éco-construction. *International Journal of*

Biological and Chemical Sciences, **11**, 499. https://doi.org/10.4314/ijbcs.v11i1.40

[35] Zoma, F., Yonli, F.H., Malbila, E., Toguyeni, D.Y.K. and Hassel, I.B. (2020) Adding Hydrated Lime in a Material Made of Clayey Soil and Fibres: Formulation and Effects on Thermo-Mechanical Properties. *Journal of Minerals and Materials Characterization and Engineering*, **8**, 149-161. https://doi.org/10.4236/jmmce.2020.83010

[36] Miller, C.J. and Rifai, S. (2004) Fiber Reinforcement for Waste Containment Soil Liners. *Journal of Environmental Engineering*, **130**, 891-895. https://doi.org/10.1061/(asce)0733-9372(2004)130:8(891)

[37] Tang, C., Shi, B. and Zhao, L. (2010) Interfacial Shear Strength of Fiber Reinforced Soil. *Geotextiles and Geomembranes*, **28**, 54-62. https://doi.org/10.1016/j.geotexmem.2009.10.001