



ORIGINAL RESEARCH ARTICLE

INFLUENCE OF BAMBOO FIBRE ON ENGINEERING PROPERTIES OF LATERITIC SOILS AS HIGHWAY PAVEMENT MATERIALS

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ABSTRACT

Lateritic soils commonly used in road pavement construction often exhibit inadequate strength and excessive plasticity, leading to poor performance under traffic and environmental loads. The study investigated bamboo fibre's (BF) ability to stabilize lateritic soils. The natural lateritic soils used were classified as clayey gravel and A-2-6(0) according to Unified Soil Classification System and AASHTO respectively. They were treated with 0 – 1.0 % (at 0.25% increment) of BF by dry weight of the soil. Liquid limit decreases with increase in fibre up to 0.5%, plastic limits decreased with increase in BF content but rises at 1%, while the plasticity index (PI) decreased with increased BF content up to 0.5% and increases at higher BF content. Maximum dry density increases with increased fibre contents to maximum of 2.207 g/cm³ and 2.092 g/cm³ at 0.75% for heavy and light compaction respectively and decreases with further fibre increment. Optimum moisture content decreased continually for all compaction efforts with higher fibre contents. Generally, soaked and unsoaked CBR increases from 15-25% and 20 - 29% (from 0-0.75% fibre) and slightly decrease at 1.0%, while UCS of the treated soil increased from 1130 to 2000 KN/m² at (0-0.50% fibre contents). The UCS-CBR developed relationships were of the second order polynomial form with R² values of 0.89 and 0.97 for soaked and unsoaked conditions respectively. The statistical analysis ($F_{cal} > F_{crit}$) confirmed significant effects of BF on soil properties. Overall, 0.75% BF provided optimal improvement and is recommended for use in sub-base layers of road pavements. Long-term durability and field performance were not evaluated; therefore, further in-situ validation is required.

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1.0 Introduction

Examining bamboo fibre's stabilizing capacity in lateritic soils was prompted by the rising expense of traditional stabilizing agents and the necessity of economically utilizing wastes for advantageous highway construction projects. The method of stabilizing soil is blending or combining the soil with chemicals or other stabilizing agents like agricultural wastes to increase its physical qualities, such as strength and durability. The different types of methods used for soil stabilization include chemical stabilization, bitumen and the environmentally friendly method of employing geotextiles and geosynthetic fibres (Afrin, 2017; Sabzi, 2018; Ogundare, 2018). Geosynthetics are products composed of several kinds of polymers, which can be woven or not (Huang et al., 2021). These are applied to improve the properties of soil and have given rise to a workable, cost-effective method of civil engineering construction. The behaviour of plant roots, which strengthens near-surface soils with low effective stress, is comparable to how fibres are used in soil and improve soil stability. Consequently Hejazi et al. (2012) reported that positive findings from laboratory and a few in-situ test results have demonstrated the possible application of fibres for soil mass reinforcement. Improving soil mass stability is the main goal of its reinforcement since it makes the soil more resilient to shear failure and deformation. Numerous reinforcing approaches are already available to stabilize problematic soils (Ogundare et al., 2018; Kramar and Gonzalez-Benito, 2022).

Chemical and mechanical approaches are the two basic ways of producing bamboo fibres. The former involves breaking down of the fibre using abrasive chemicals and extrudes it through mechanical spinnerets, mimicking the viscose process used to manufacture rayon (Kramar and Gonzalez-Benito, 2022; Joshi and Bhattacharyya, 2011). The process of producing Lyocell fibres employs the closed solvent spinning cycle. Engineering structures such as paved roads and buildings impose loads on the soils on which they are constructed. These soils are therefore required to have a bearing capacity sufficient to withstand these loads. Uganda road network is mostly composed of lateritic soil layered roads, due to clayey property of these soils and having hard top and weak bottom, are capable of absorbing and retaining an appreciable amount of water, making them slippery when it rains. In the long run, the roads develop potholes, and heave as a result of heavy traffic and detainment of water in the soils (Ali *et al.*, 2011).

Cement and lime have been the two primary materials utilized to improve the engineering qualities of soil over the years, (Consoli *et al.*, 2009). By burning fossil fuels to provide the energy needed for the cement manufacturing process, the cement-lime subsector contributes approximately 7% of worldwide CO₂ emissions to the environment and requires between 12 and 15% of all industrial energy, (Ali *et al.*, 2011; Oh, *et al.*, 2014; Schneider, 2019). Global warming is one of the detrimental repercussions this has on the environment and the future of humanity. In addition to this, some cement bags currently produced are a threat to the environment since they are non-biodegradable, which is environmentally hazardous, (Podder *et al.*, 2020). The technique of stabilizing soil using geosynthetics can be effectively used to meet the challenges of the society such as the increasing prices of cement and excessive use of natural resources like limestone. Cement production is also attributed to release of carbon dioxide into the atmosphere which leads to global warming. Therefore, use of bamboo fibre, as a stabilizer for lateritic soils will reduce the problem of costs and environmental concerns related to the use of cement as a stabilizer. The strength parameters of the natural soil may be enhanced by adding bamboo fibres, which would lessen the thickness of the pavement layer and the amount of stress on the subgrade. The bamboo fibre is one of the agro-waste materials that is widely accessible, inexpensive and environmentally beneficial (Gowthaman *et al.*, 2018). Thus, this study was aimed at investigating the effect of bamboo fibres on engineering properties of laterite soils as material for road pavement construction.

2. Materials and Method

2.1 Research Design

The research used experimental matrix method to predict the outcome of using different material combinations to get variations and hypothesize variable results. It also planned for the delivery of the experiment under statistically optimal conditions given the constraints of available resources. The arrangement of the deed carried out is summarized as shown in Figure 1.

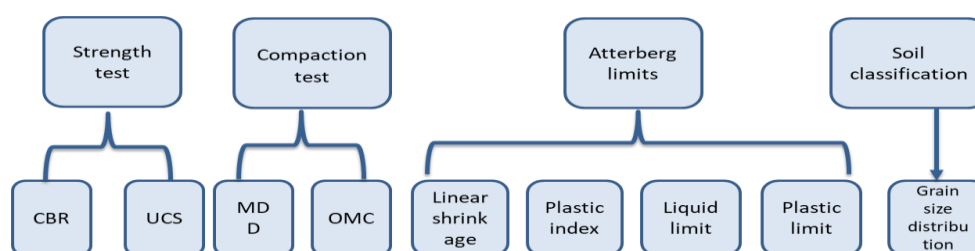


Figure 1: Research Test Design

2.2 Materials

2.2.1 Soil samples

Bulk samples of the yellowish-brown lateritic soil were obtained by disturbed sampling from a borrow pit at a depth of 2.0 - 3.0 m along Kabaraga on the Kabale–Mbarara Road in Kabale District, Uganda. Sampling at this depth follows common geotechnical/soil engineering practice, as soils beyond the upper 1.5 m are less affected by organic matter, surface leaching, and anthropogenic disturbance, and therefore provide more representative materials for geotechnical evaluation in line with BS 1377-1 (2016) and ASTM D1452-16 (2016). After transporting materials to the laboratory, the samples were air-dried for two days to reduce natural moisture content and ensure uniformity before pulverization and testing. Air-drying is consistent with standard

specimen preparation guidelines, which recommend drying at ambient temperature to avoid alteration of soil structure or mineralogy that may occur during oven drying (BS 1377-1, 2016; ASTM D421, 2007). The dried soil was manually broken down to pass through the appropriate sieve size prior to laboratory testing.

2.2.2 Bamboo fibre

The bamboo used in this study was sourced from a plantation in Bwera–Kasese, Uganda. To obtain the fibres, the bamboo culms were soaked in a sodium hydroxide (NaOH) solution for 1–2 days. The alkali-treatment method is widely adopted for natural fibre extraction and modification because NaOH helps remove lignin, hemicellulose, and surface impurities, thereby increasing fibre roughness and enhancing bonding with soil particles. This was done in line with guidelines for fibre surface treatment by (Li et al., 2007; ASTM D790-17, 2017). After treatment, the fibres were washed, cut into approximately 1.0 cm lengths, and air-dried to a stable condition as shown in Plate I. The fibre length was selected based on previous studies indicating that short discrete natural fibres within the range of 1–2 cm improve soil reinforcement efficiency and promote uniform fibre distribution (Consoli et al., 2010). Test specimens were prepared by incorporating 0%, 0.25%, 0.5%, 0.75%, and 1.0% bamboo fibre (by dry weight of soil) in 0.25% increments.



Plate I: Bamboo Fibre Sample Preparation

2.3 Method

In compliance with the procedures described in (BS 1377, 1990; BS 1942, 1990) and standard ASTM codes, the index properties, particle size distribution, soil classification, specific gravity, water absorption, compaction characteristics, California bearing ratio, and unconfined compressive strength of lateritic soil samples were determined. In order to stabilize the lateritic soil, bamboo fibre was added in steps of 0.25% by weight of dry soil.

2.3.1 particle size distribution

In order to classify the particles into distinct size ranges and ascertain the proportion by mass of each size range, the soil underwent particle size distribution in accordance with (Salter, 1979; Head, 1992; ASTM, D6913 – 04, 2009). A soil sample was run through progressively decreasing mesh sizes in order to accomplish this. The cumulative proportion by weight passing each filter was computed using the weight of the soil sample kept on each sieve (ASTM D5319 – 97, 2008; Craig, 1992).

2.3.2 Specific gravity

Samples of soil-BF mixes, bamboo fibre, and oven-dried soil weighing between 50 and 100g were sieved using a sieve with an aperture of 2.36 mm. Next, the mixture's specific gravity was ascertained by applying the techniques outlined in (ASTM C127 – 07, 1994).

2.3.3 Atterberg limits

Between 50 and 100 g of oven-dried soil, bamboo fibre, and soil-BF mix samples were sieved using a sieve with a 2.36 mm sieve aperture. Then, using the techniques outlined in (ASTM D4318 – 10, 1994), the mixture's specific gravity was determined. To ascertain the cohesiveness and plasticity of the soil-bamboo fibre mixtures, these experiments were performed on each mixture.

2.3.4 Compaction characteristics

The process of reducing the air spaces in the soil to make it denser is called compaction. Its objective is to determine the soil's optimum moisture content (OMC) and maximum dry density (MDD) (Nayak and Mishra, 2016). Materials with a high MDD with a relatively low moisture content are frequently suitable for fill embankments as well as sub-grade, sub-base, or base course. To reproduce the expected compaction energy encountered in the field and for comparative purposes, the British standard light (BSL) and heavy (BSH) compaction methods were used in this experiment to establish the OMC corresponding to the MDD (ASTM D698-07el, 1994; Daniel and Wu, 1993).

2.3.5 California bearing ratio and unconfined compressive strength tests

The California Bearing Ratio (CBR) test for the soil–bamboo fibre mixtures was performed in accordance with the ASTM D1883-16 (2016) standard. The CBR value is determined at penetrations of 2.5 mm and 5.0 mm, and the higher of the two values is adopted as the CBR of the specimen, as specified in the ASTM D1883-16 (2016) standard. The unconfined compressive strength technique was carried out by applying an increasing load to prepared specimens (mixed, compacted, and cured) until failure, the strength of the stabilized material was ascertained. Plastic bags were used to keep carriers and specimens airtight in a water bath which ideally keeps temperatures at or around 25 °C in accordance with (BS 1377, 1990 and BS 1924, 1990), for natural and modified soil samples respectively.

3. Results and Discussion

3.1 Results of Preliminary Test on the Natural Soil

Table 1 and Figure 2, respectively, display the engineering parameters of the natural soil and the sieve analysis results.

Table 1: Engineering Properties of Natural Laterite Soil Used

| Property | Quantity |
|---|---------------------------------|
| Liquid limit (LL) % | 39.4 |
| Plastic limit (PL) % | 20 |
| Plasticity index (PI) % | 19.4 |
| AASHTO classification | A-2-6 |
| Unified Soil Classification Systems (USCS) | Silty or Clayey Gravel and Sand |
| Group index | 0 |
| Color | Reddish-Brown |
| Maximum dry density at Heavy compaction (MDDH), g/cm ³ | 1.923 |
| Maximum dry density at Light compaction (MDDL), g/cm ³ | 1.980 |
| Optimum moisture content at Heavy compaction (OMCH) % | 15.7 |
| Optimum moisture content at Light compaction (OMCL) % | 12.6 |
| California Bearing Ratio (CBR) % (Soaked) | 15 |
| California Bearing Ratio (CBR) % (Unsoaked) | 20 |
| Unconfined Compressive Strength (UCS), KN/m ² | 1130 |

According to the AASHTO classification system, the natural soil sample may be broadly classified as silty or clayey gravel and sand soil based on the engineering parameters in Table 1 and fell within group classification A-2-6(0). This is in line with research by Ola (1983), which claims that the A-2, A-6, and A-7 groups comprise the majority of lateritic soils used for road construction. The soil contains notable amounts of clay material elements, as well as some sand and gravel material constituents. The results in Table 1 and Figure 2 indicated

that the soil samples had a lower percentage of fractions finer than 0.075, (that is, % Passing 0.075 mm sieve of $0.3\% < 35\%$), LL of $39.4\% < 40\%$, and PI of $20\% > 11\%$ while passing through a 0.075 mm sieve. As a result, the soil is categorized as A-2-6(0), and (AASHTO, 1986) rates the general sub-grade as excellent to good. The natural soil underwent a compaction test, yielding maximum dry densities of 1.923 g/cm^3 at heavy compaction (MDDH) and 1.980 g/cm^3 at light compaction (MDDL). The corresponding optimum moisture contents at heavy compaction (OMCH) and light compaction (OMCL) were 15.7% and 12.6%, respectively. The soaked California Bearing Ratio (CBR) was 15.36%, and the unsoaked California Bearing Ratio (CBR) was 19.89%. It was determined that the unconfined compressive strength was 1130 kN/m^2 .

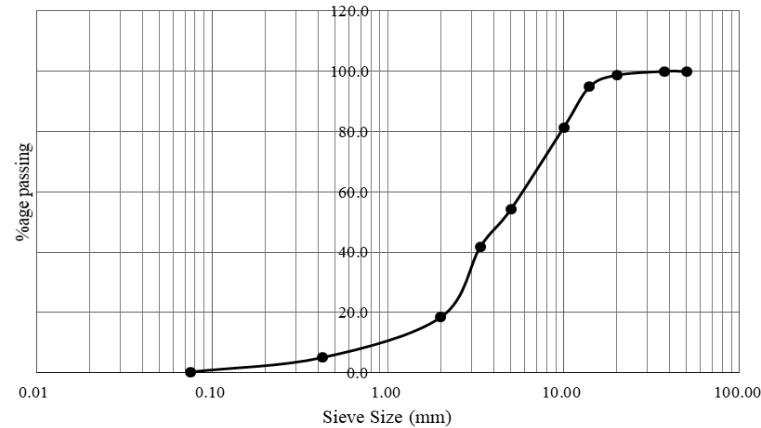


Figure 2: Particle Size Distribution Graph

3.1.1 Specific density of bamboo fibre treated soil

From the results presented in Figure 3, the specific gravity of the soil showed slight fluctuations with increasing bamboo fibre content. The measured values were 2.61, 2.51, 2.60, 2.50, and 2.66 for 0%, 0.25%, 0.50%, 0.75%, and 1.0% fibre contents respectively. Although no clear linear trend was observed, this behaviour is consistent with previous findings on natural fibre - soil mixtures, where the introduction of low-density organic fibres can produce non-uniform changes in specific gravity depending on fibre distribution and interaction with soil minerals (Li *et al.*, 2007; Consoli *et al.*, 2010). Bamboo fibres generally have lower density than mineral soils; therefore, slight increases or decreases in specific gravity may result from localized clustering of fibres or incomplete bonding at certain replacement levels.

The implication of this behaviour is that specific gravity alone may not be a reliable indicator of the effectiveness of fibre stabilization, since the mechanical improvements observed in terms of strength (CBR and UCS) are governed more by fibre-soil interlocking and reinforcement effects than by changes in particle density. Thus, the irregular variations in specific gravity do not adversely affect the stabilization outcome but reflect the natural variability associated with incorporating organic fibres into soil matrices.

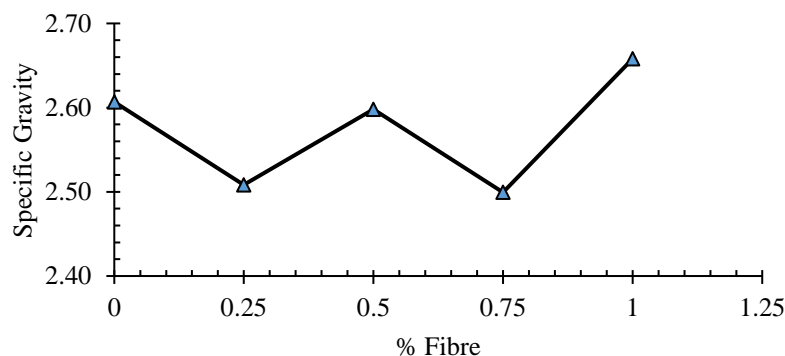


Figure 3: Specific Gravity Versus % Fibre

3.1.2 Water absorption of bamboo fibre treated soil

The water absorption results, as presented in Figure 4, show a generally increasing trend with higher bamboo fibre content, except for a slight decrease observed at 0.50% fibre. The overall increase in water absorption can be attributed to the hygroscopic nature of bamboo fibres, which possess internal voids and cellulose-based

structures capable of retaining moisture. Similar observations have been reported in studies involving natural fibre-soil composites, where fibres absorb part of the pore water and consequently alter the soil's moisture distribution (Li et al., 2007). The slight drop at 0.50% fibre may be linked to improved fibre–soil interlocking at this specific content, which reduces the number of open voids available for water infiltration. Consoli et al. (2010) also noted that when fibres are more uniformly dispersed at certain proportions, they can fill microvoids within the soil matrix, temporarily reducing overall water uptake.

This behaviour implies that water absorption characteristics in fibre-stabilized soils are highly sensitive to both fibre content and distribution. Higher absorption at elevated fibre percentages may influence compaction behaviour and optimum moisture requirements, while the temporary reduction at 0.50% suggests that there may be an optimum fibre range where moisture-related effects are minimized, potentially contributing to better mechanical performance. This highlights the need to consider both hydrophilic properties of fibres and their dispersion within the soil when designing fibre-stabilized pavement materials.

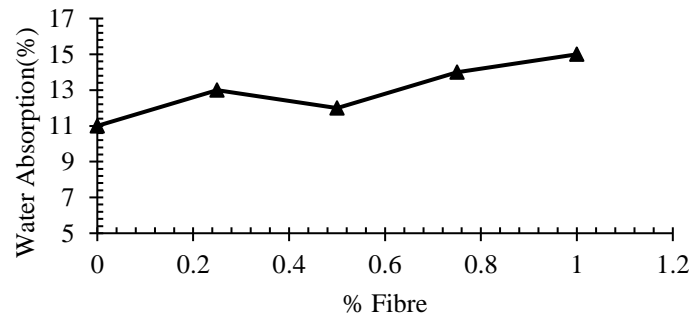


Figure 4: Water Absorption Against % Fibre

3.1.3 Influence of bamboo fibre on atterberg limits of lateritic soils

The impact of bamboo fibres on the Atterberg limits (consistency tests) of laterite soils and its trends are shown in Table 3 and Figures 5–7. The ranges for the liquid limit, plastic limit, and plasticity index are 36.0% to 40.3%, 16.4% to 20.0%, and 19.1% to 21.2%, respectively.

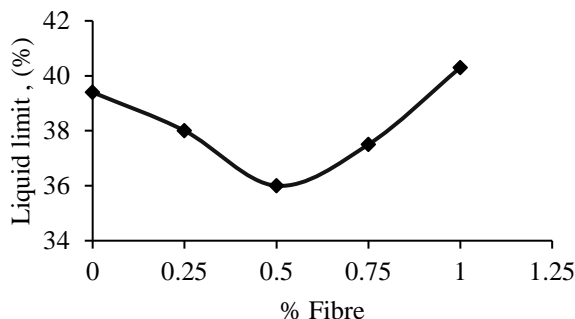


Figure 5: Liquid Limit Versus % Fibre

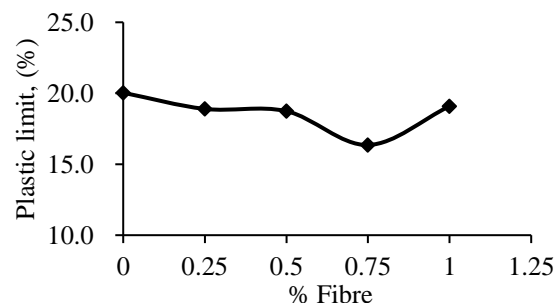


Figure 6: Plastic Limit vs % Fibre

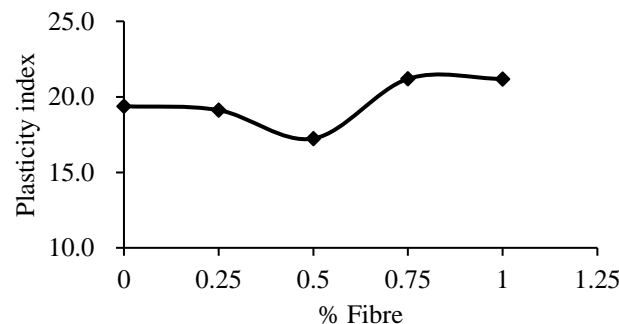


Figure 7: Plasticity Index Versus Percentage Fibre

Close look at Figures 5-7 indicated that the Atterberg Limits results do not have a specific pattern but the liquid limit and plastic limit decreased with increment in fibre content from 0 to 0.5% and from 0 to 0.75 % then experience a slight increase for 0.75 and 1.0% fibre content. On the other hand, the plasticity index decreases up to 0.5% fibre and became constant for 0.75 and 1.0%. The friction forces of resistance that formed between the soil and the bamboo fibre, which acted as a reinforcing material, may be accountable for the decrease in LL and PL. At 0.5% fibre content, the bamboo fibres are likely optimally dispersed within the soil, reducing the soil's overall plastic activity and leading to lower LL and PI. Beyond this point, excess fibres

may clump together, trap water, and interfere with soil structure, causing LL and PI to rise again. This reflects the transition from effective reinforcement to fibre-induced interference in the soil matrix.

3.2 Strength Characteristics of Bamboo Fibre Treated Soil

3.2.1 Compaction characteristics results

Tables 2 - 3 and Figures 8 – 11 presents the compaction results for both MDD and OMC with varying bamboo fibre in soil by percentage.

Table 2: Compaction Results for Treated Soil Samples with Varying Percentage Fibre

| Light Compaction Results for Treated Soil Samples | | | | | | | | | |
|---|-------|--------|--------|--------|-------|--------|-------|--------|-------|
| 0% | | 0.25% | | 0.50% | | 0.75% | | 1.00% | |
| DD | A.MC | DD | A.MC | DD | A.MC | DD | A.MC | DD | A.MC |
| 1.9 | 11.2 | 1.812 | 9.265 | 9.265 | 1.780 | 8.849 | 1.943 | 7.785 | 1.934 |
| 1.9 | 11.8 | 1.928 | 10.234 | 10.234 | 1.914 | 9.278 | 2.013 | 8.528 | 2.009 |
| 2 | 12.6 | 2.016 | 11.333 | 11.163 | 2.024 | 10.045 | 2.086 | 9.434 | 2.111 |
| 1.9 | 13.4 | 1.923 | 13.371 | 12.246 | 1.969 | 11.786 | 2.013 | 11.980 | 1.996 |
| 1.8 | 14.2 | 1.828 | 14.036 | 14.067 | 1.802 | 12.869 | 1.927 | 12.990 | 1.934 |
| Heavy compaction results for treated soil samples | | | | | | | | | |
| 13.172 | 1.860 | 8.673 | 1.813 | 8.889 | 1.883 | 9.144 | 1.906 | 8.352 | 1.855 |
| 14.152 | 1.892 | 11.566 | 1.923 | 11.047 | 1.945 | 10.485 | 1.973 | 9.516 | 2.059 |
| 15.708 | 1.923 | 14.130 | 1.980 | 13.288 | 1.999 | 11.829 | 2.034 | 9.965 | 2.128 |
| 16.697 | 1.898 | 15.073 | 1.938 | 15.873 | 1.920 | 14.506 | 1.947 | 11.320 | 2.030 |
| 17.190 | 1.882 | 16.360 | 1.856 | 17.072 | 1.875 | 16.071 | 1.900 | 12.91 | 1.847 |

Note: DD = Dry Density, A.MC = Average Moisture Content

With reference to Figures 8 and 9, it was shown that, in general, the optimal moisture level falls as the maximum dry density increases with increasing fibre content up to 0.75% and then declines at 1.0% bamboo fibre. It is believed that when bamboo fibre content rises, the desire for water decreases, resulting in a decreased optimal moisture content.

The fibre binds the soil together and restricts the amount of pore space available for soil expansion and absorption, and speeds up the rate at which the soil absorbs water. The creation of "transitional compounds" by molecular rearrangement may be the cause of the rise in the maximum dry density of soil-bamboo fibre content which agreed with the studies of (Adefemi and Wole, 2013). A further rise in the MDD is thought to be caused by the clay particles flocculating and aggregating in the soil and taking up greater spaces, which increases the volume of the voids. As a result, lowers the weight to volume ratio and, ultimately, lowers density. The results obtained is in agreement with the studies conducted by (Alhassan, 2008).

Table 3: MDD and OMC Results of the Bamboo Fibre Treated Soil

| MDD Results of the Bamboo Fibre Treated Soil | | |
|--|---------------------------------------|---------------------------------------|
| Fibre (%) | MDD _H (g/cm ³) | MDD _L (g/cm ³) |
| 0 | 1.923 | 1.980 |
| 0.25 | 1.975 | 2.020 |
| 0.50 | 1.985 | 2.023 |
| 0.75 | 2.207 | 2.092 |
| 1.0 | 2.105 | 2.000 |
| OMC Results of the Bamboo Fibre Treated Soil | | |
| Fibre (%) | OMC _H (%) | OMC _L (%) |
| 0 | 15.7 | 12.6 |
| 0.25 | 13.81 | 11.9 |
| 0.50 | 13.40 | 11.4 |
| 0.75 | 11.80 | 10.4 |
| 1.0 | 10.20 | 9.8 |

Subscript H stands for heavy compaction while subscript L is for light compaction

For Heavy compaction, the MDD was found to increase from 1.923 g/cm³ for natural soil to 1.975 g/cm³ at 0.25 %, it later increase at 0.5% content and dropped at 1.0% fibre with its OMC reducing from 15.7 % to

13.81 % at 0.25 % and finally to 10.2 % at 1.0 % fibre as shown in Table 3 and Figure 10 – 11, whereas, for Light compaction, it was observed that the MDD increased to its peak of 2.092% at 0.75 % content and it dropped to 2.000 g/cm³ at 1.0% respectively.

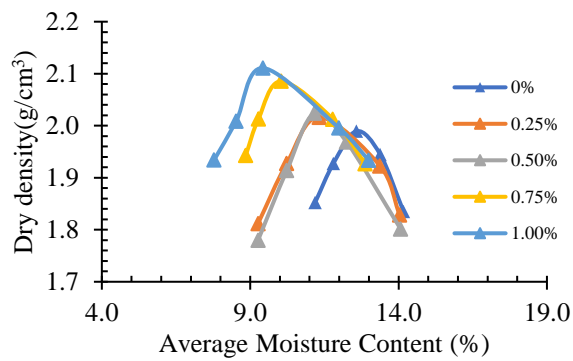


Figure 8: Dry Density Against Moisture Content for Light Compaction

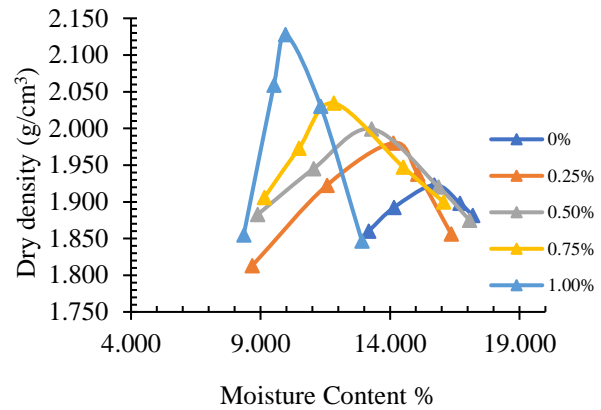


Figure 9: Dry Density Against Moisture Content for Heavy Compaction

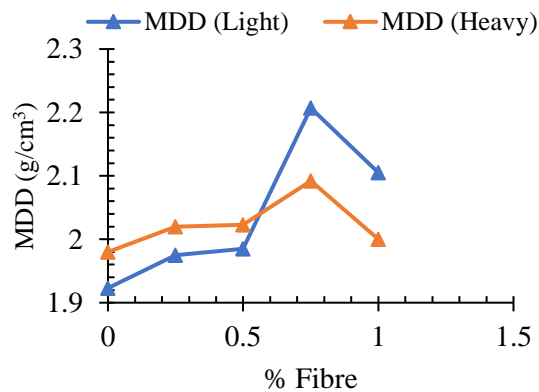


Figure 10: Effect of % Fibre on MDD

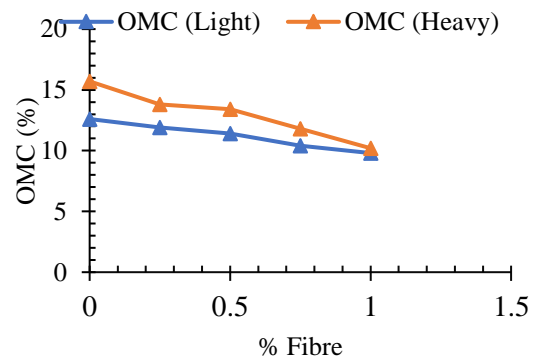


Figure 11: Effect of % Fibre on OMC of Treated Soil

3.2.2 California Bearing Ratio (CBR) Test Results

Figure 12 present the CBR results for both soaked and unsoaked conditions with varying bamboo fibre contents in soil by percentage.

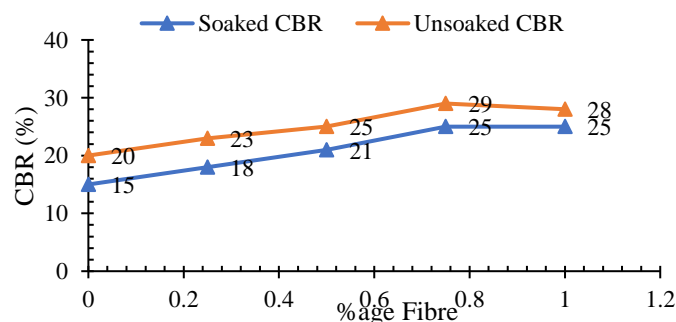


Figure 12: Effect Of Percentage Fibre on Soaked and Unsoaked CBR of Lateritic Soil

The CBR of the soil increased as the fibre content increased for both soaked and unsoaked conditions and it was observed that for unsoaked CBR it dropped beyond 0.75%, while for soaked it had a minimal increase beyond that value with the high gradual increase between 0.5 and 0.75% as shown in Figure 12. The soaked CBR increased gradually from 15, 18, 21 and 25% then became constant 25% at 0, 0.25, 0.5%, 0.75 and 1.0% respectively. However, the unsoaked CBR was observed to be greater than soaked and gradually increased with the increase of fibre content from 20, to 23 to 25 to 29% and dropped to 28% at 0, 0.25, 0.5, 0.75 and 1.0% fibre contents respectively.

3.2.3 Effect of BF on unconfined compressive strength of lateritic soil

Unconfined Compressive Strength (UCS) of treated soil at varying bamboo fibre contents was evaluated. It was observed that the UCS of the laterite soil gradually increased till maximum of 2.00 MPa at 0.75% fibre replacement and thereafter it dropped at 1.0% fibre as shown in Figure 13.

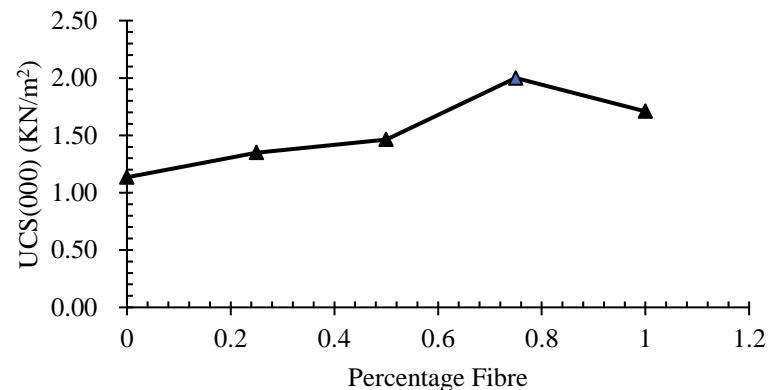


Figure 13: Effect of Percentage Fibre on UCS

The results showed that when the amount of bamboo fibre (BFC) increases, the UCS also increases until it reaches optimum at 0.75%. At the point, further addition of the bamboo fibre does not improve the mechanical properties of the soil. The highest strength properties at OMC were noted when the bamboo fibre concentration was higher than 0.75%. Additionally, as the amount of bamboo fibre rose, the stress-strain curve tended to have a steeper slope at high water content.

3.2.4 Development of strength characteristics relationship

Figures 14 and 15 present a graphical representation of UCS – CBR (soaked and unsoaked) correlations while equations 1 and 2 indicate the graphical developed relationships. Tables 4 and 5 present the ANOVA analysis results, while Equations 3 and 4 presents the regression statistical models developed.

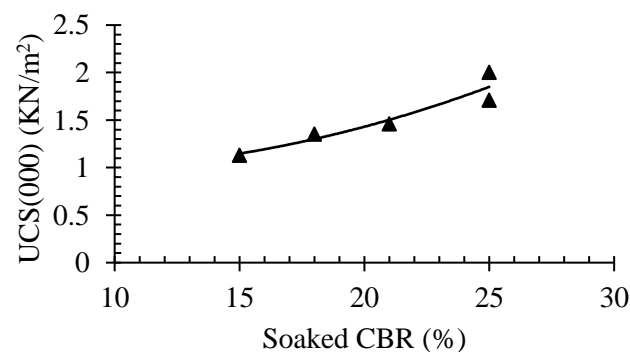


Figure 14: UCS against Soaked CBR

$$\text{UCS}_p = 0.0027\text{CBR}_s^2 - 0.0388\text{CBR}_s + 1.1162 \quad (1)$$

$$R^2 = 0.8963$$

where; UCS_p = Unconfined Compressive Strength at Fibre Content, CBR_s = Soaked California Bearing Ratio (CBR) at Fibre Content.

Models were formulated using UCS results as dependent variables, with CBR results as the independent variables as shown on Figures 14 and 15, Equations 1 and 2 respectively. Strength indices tests results were used in running the ANOVA analysis, while the validity of the correlation was established using R^2 values being close to ± 1 . A strong relationship between CBR and UCS is indicated by the fact that all of the models fit into a second order polynomial equation of the form $\alpha_1 x^2 - \alpha_2 x + c$, with R^2 values of 0.967 and 0.896 for drenched and unsoaked situations, respectively.

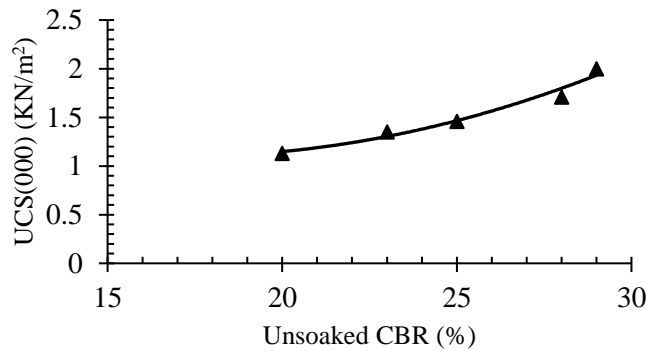


Figure 15: UCS against Unsoaked CBR

$$UCS_P = 0.0059CBR_{US}^2 - 0.2021CBR_{US} + 2.8281 \quad (2)$$

$$R^2 = 0.967$$

where; UCS_P = Unconfined Compressive Strength at each Fibre Content, CBR_{US} = Unsoaked California Bearing Ratio (CBR) values at varying Fibre Content.

Table 4: Summary of Regression Analysis for the Soaked CBR

| | df | SS | MS | F | Significance F |
|------------|----|-------------|-----------|------------|----------------|
| Regression | 3 | 0.448094683 | 0.1493649 | 59.6191638 | 0.094851212 |
| Residual | 1 | 0.002505317 | 0.0025053 | | |
| Total | 4 | 0.4506 | | | |

| | Coefficients | Standard Error | t Stat | P-value | Lower 95% | Upper 95% |
|-----------|--------------|----------------|-----------|------------|--------------|-------------|
| Intercept | -3.976480858 | 0.98922661 | -4.019788 | 0.15522068 | -16.54579669 | 8.592834973 |
| OMC | 0.046814369 | 0.040899195 | 1.1446281 | 0.45713293 | -0.472859173 | 0.566487911 |
| MDD | 1.915224476 | 0.549055349 | 3.4882175 | 0.17773894 | -5.061185203 | 8.891634155 |
| CBR | 0.047768943 | 0.02695943 | 1.7718825 | 0.32710161 | -0.294783096 | 0.390320982 |

$$UCS_P = 0.05OMC_P + 1.92MDD_P + 0.05CBR_P - 3.98 \quad (3)$$

where; $UCSP$ = Unconfined Compressive Strength at each Fibre Content, $OMCP$ = Optimum moisture content (OMC) values at each Fibre Content, $MDDP$ = Maximum Dry Density (MDD) values at each Fibre Content and $CBRP$ = California Bearing Ratio (CBR) values at each Fibre Content. The regression analysis was conducted using UCS results as dependent variables, with OMC, MDD and CBR results as the independent variables as shown in Equations 3 and 4 respectively. Strength indices tests results used were validated using R^2 being close to 1 and $F > F_{Significant}$, which indicate a good correlation between the engineering properties and also indicating that the effect of bamboo fibre on lateritic soil is statistically significant. This was done to lessen the rigors of laboratory work, which allows for result estimation and saves time and energy. It also helps to facilitate the application of laboratory data and acts as a guide in predicting relationships between variables.

Table 5: Summary of Regression Analysis for the Unsoaked CBR

| | df | SS | MS | F | Significance F |
|------------|----|----------|----------|----------|----------------|
| Regression | 3 | 0.450234 | 0.150078 | 410.3028 | 0.0362712 |
| Residual | 1 | 0.000366 | 0.000366 | | |
| Total | 4 | 0.4506 | | | |

| | Coefficients | Standard Error | t Stat | P-value | Lower 95% | Upper 95% |
|-----------|--------------|----------------|----------|----------|-----------|------------|
| Intercept | 4.215877346 | 0.369173 | -11.4198 | 0.055605 | -8.906668 | 0.47491359 |
| OMC | 0.058727336 | 0.009361 | 6.273921 | 0.100624 | -0.06021 | 0.17766437 |
| MDD | 1.977209634 | 0.173602 | 11.38932 | 0.055753 | -0.228613 | 4.18303234 |
| CBR | 0.046433624 | 0.004012 | 11.57262 | 0.054875 | -0.004548 | 0.09741562 |

$$\text{UCS}_P = 0.06\text{OMC}_P + 1.98\text{MDD}_P + 0.05\text{CBR}_P - 4.22 \quad (4)$$

3.2.5 Determination of the optimal bamboo fibre stabilized soil

Peak value for the strength characteristics (unsoaked CBR, soaked CBR, and unconfined compressive strength) of soil were recorded at 0.75% fibre content. Table 6 compares the results obtained from the optimum bamboo fibre treated soil with sub-base requirements of (MoWHC, Uganda, 2010), and it was concluded that lateritic soil stabilized with bamboo fibre at 0.75% can be used for road sub-base construction.

Table 6: Evaluation of the Lateritic Soil Stabilized at Optimum Bamboo Fibre

| Ministry of Works, Housing and Communication of Uganda, Sub-base material requirements, 2010 | | | |
|--|--------------------|-------------|---------|
| Properties | Fibre Treated Soil | Requirement | Comment |
| LL (%) | 37.5 | 40-46.5 | Not Ok |
| PI (%) | 21.2 | 12-25 | Ok |
| OMC (%) | 11.8 | <9.4 | Not Ok |
| MDD (kg/m ³) | 2027 | < 2073 | Ok |
| Soaked CBR (%) | 25 | >15 | Ok |
| Unsoaked CBR (%) | 29 | NA | NA |
| UCS (KN/m ²) | 2000 | NA | NA |
| %age passing 37.5mm | 100 | >95 | Ok |

4. Conclusion

The degree to which the presence of bamboo fibre in soil can enhance both its mechanical and physical qualities has been assessed in this study. This study demonstrated how stabilizing lateritic soil during the construction of road pavement is achievable by using bamboo fibre as a stabilizing material. The study's findings were used to determine the soil's index qualities, including its particle size distribution, liquid limit, plastic limit, and plasticity index. The soil was then categorized using the AASHTO classification system as A-2-6 and as silty or clay gravel and sand. The maximum dry density (MDD) of the treated lateritic soil with bamboo fibre increased generally up to 0.75% fibre for both light and heavy compaction and decreased at 1.0% fibre content. The optimum moisture content (OMC) likewise decreased. The CBR values for both soaked and unsoaked conditions showed increase up to 0.75% fibre content and then decrease for unsoaked while for soaked CBR it remained constant after 0.75% fibre. There was also an improvement in the UCS of 2.00 Mpa at 0.75% fibre content. Second order polynomial relationships were developed between UCS and soaked CBR and unsoaked CBR with R^2 values of 0.896 and 0.967 respectively indicating a good correlation. For the regression analysis conducted with the strength properties at varying fibre contents, the R^2 values were 0.9967 and 0.9777 respectively, in each case having $F_{cal} > F_{crit}$. These are indications that the effect of bamboo fibre on engineering properties of lateritic soil is statistically significant and not a mere occurrence. In comparison with Uganda MoWH&C (2010), laterite soil optimally stabilized at 0.75% fibre meets the requirement for construction of sub-base layer material of road pavement. Long-term durability and field performance were not evaluated; therefore, further in-situ validation is required.

References

- AASHTO. 1986. Standard specification for transportation materials and methods of sampling and testing. 14th Edition, American Association of State Highway and Transportation Officials: Washington.
- Adefemi, BA. and Wole, AC. 2013. Regression analysis of compaction delay on CBR and UCS of lime stabilized yellowish brown lateritic soil. *EDGE*, 18: 1–14.
- Afrin, H. 2017. A review on different types soil stabilization techniques. *International Journal of Transportation Engineering and Technology*, 3(2):19–24. DOI: 10.11648/j.ijtet.20170302.12.
- Alhassan, M. 2008. Potentials of rice husk ash for soil stabilization. *AU Journal of Technology*, 11(4): 246–250.
- Ali, M.B., Saidur, R. & Hossain, M.S. 2011. A review on emission analysis in cement industries. *Renewable and Sustainable Energy Reviews*, 15(5): 2252–2261.

Alrubaye, A. J., Hasan, M., & Fattah, M. Y. 2016. Engineering properties of clayey soil stabilized with lime. *ARPJN Journal of Engineering and Applied Sciences*, 11(4): 2434–2441.

ASTM C127–07. 1994. Standard test method for density, relative density (specific gravity), and absorption of coarse aggregate. *ASTM, Annual Book of ASTM Standards*, 4(2): 6.

ASTM D 4318–10. 1994. Standard test methods for liquid limit, plastic limit, and plasticity index of soils. *ASTM, Annual Book of ASTM Standards*, 04(02): 1–16.

ASTM D1883-07e2. 1994. Standard test method for CBR (California Bearing Ratio) of laboratory-compacted soils. *ASTM, Annual Book of ASTM Standards*, 04(2): 1–9.

ASTM D421-85. 2007. Standard Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants. *ASTM International*, West Conshohocken, PA.

ASTM D5319–97. 2008. Standard specification for glass-fibre reinforced polyester wall and ceiling panels. *ASTM, Annual Book of ASTM Standards*, 04(02): 4.

ASTM D6913–04. 2009. Standard test methods for particle-size distribution (gradation) of soils using sieve analysis. *ASTM, Annual Book of ASTM Standards*, 04(02): 1–34.

ASTM D698-07e1. 1994. Standard test methods for Laboratory compaction characteristics of soil using standard effort. *ASTM, Annual Book of ASTM Standards*, 04(02): 1–13.

ASTM D1452-16. 2016. Standard Practice for Soil Exploration and Sampling by Auger Borings. *ASTM International*, West Conshohocken, PA.

ASTM D1883-16. 2016. Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils. *ASTM International*, West Conshohocken, PA.

ASTM D790-17. 2017. Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. *ASTM International*, West Conshohocken, PA.

BS 1377. 1990. Methods of test for soil for civil engineering purposes. *British Standard Institute*, London.

BS 1377-1. 2016. Methods of Test for Soils for Civil Engineering Purposes – Part 1: General Requirements and Sample Preparation. *British Standards Institution*, London.

BS 1924. 1990. Methods of test for stabilized soils. *British Standard Institute*, London.

Consoli, N. C., da Silva L. L., Foppa, D., & Heineck, K. S. 2009. Key parameters dictating strength of lime/cement-treated soils. *Proc. Inst. of Civil Engineers – Geotechnical Engineering*, 162(2): 111–118.

Consoli, NC., Casagrande, MDT. and Coop, MR. 2010. Effect of fibre reinforcement on the isotropic compression behaviour of a sandy soil. *Geotextiles and Geomembranes*, 28(4): 344–351.

Craig, RF. 1992. *Soil Mechanics*, 5th Edition, Chapman and Hall, London,; 27–33.

Daniel, DE. and Wu, YK. 1993. Compacted clay liners and covers for arid sites. *Journal of Geotechnical Engineering ASCE*, 119(2): 223–237.

Gowthaman, S., Nakashima, K. and Kawasaki, S. 2018. A state-of-the-art review on soil reinforcement technology using natural plant fibre materials. *Materials*, 11(4): 553. doi:10.3390/ma11040553.

Head, KH. 1992. *Manual of soil laboratory testing*, 1. Pentech Press Ltd., London.

Hejazi, SM., Sheikhzadeh, M., Abtahi, SM. and Zadhoush, A. 2012. A simple review of soil reinforcement by using natural and synthetic fibres. *Construction and Building Materials*, 30: 100–116.

- Huang, J., Kogbara, RB., Hariharan, N., Masad, EA. and Little, DN. 2021. A state-of-the-art review of polymers used in soil stabilization. *Construction and Building Materials*, 305: 124 - 685.
- James, J. and Pandian, PK. 2016. Industrial wastes as auxiliary additives to cement/lime stabilization of soils. *Advances in Civil Engineering*; 1–17. <https://doi.org/10.1155/2016/1267391>.
- Joshi, M. and Bhattacharyya, A. 2011. Nanotechnology—a new route to high-performance functional textiles. *Textile Progress*, 43(3): 155–23.
- Kramar, A. and González-Benito, FJ. 2022. Cellulose-based nanofibres processing techniques and methods based on bottom-up approach - a review. *Polymers*, 14(2): 286.
- Li, X., Tabil, LG. and Panigrahi, S. 2007. Chemical treatments of natural fibre for use in natural fibre-reinforced composites: A review. *Journal of Polymers and the Environment*, 15(1): 25–33.
- Ministry of Works and Transport (MoWHC). 2010. Road design manual, pavement design, flexible pavement, 3(1), Uganda: Ministry of Works, Housing & Commerce.
- Nayak, L. and Mishra, S. 2016. Prospect of bamboo as a renewable textile fibre. *Fashion and Textile*, 3(2): 1–23.
- Ogundare, D., Adebera, SS., Familusi, A., and Adewuni, BE. 2018. Stabilization of subgrade using geosynthetics under soaked condition. *Annals of the Faculty of Engineering Hunedoara*, 16(4): 157–162.
- Oh, DY., Noguchi, T., Kitagaki, R. and Park, WJ. 2014. CO₂ emission reduction by reuse of building material waste in the Japanese cement industry. *Renewable and Sustainable Energy Reviews*, 38: 796–810.
- Ola, SA. 1983. Tropical soils in Engineering practice. Balkema Publishers, Rotterdam.
- Poddar, T., De, N. and Sarkar, S. 2020. Efficient engineering techniques for segregation and management of non-biodegradable wastes. *International Journal of Sustainable Energy and Environmental Research*, 9(2): 123–137.
- Sabzi, Z. 2018. Environmental friendly soil stabilization materials available in Iran. *Journal of Environmental Friendly Materials*, 2(1): 33–39.
- Salter, RJ. 1979. Highway design and construction. The Macmillan Press Ltd., London.
- Schneider, M. 2019. The cement industry on the way to a low-carbon future. *Cement and Concrete Research*, 124: 105–792.