Sustainable Structures
ISSN: 2789-3111 (Print); ISSN: 2789-312X (Online)
http://www.sustain-dpl.com/journal/sust
DOI: 10.54113/j.sust.2025.000083

***ORIGINAL ARTICLE***

# Experimental study on the suitability of highland bamboo sawdust in improving expansive soil

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**Abstract:** Soils are naturally existing materials that challenges civil engineering structures such as roads and buildings. However, not all soils are suitable materials to uses due to their changing in strength and stability under fluctuating environmental conditions. Expansive soils, in particular, pose substantial challenges due to their propensity to experience considerable volumetric changes with variations in moisture content. This instability can lead to structural damage and increased maintenance costs. The study aims on improving soil's engineering properties using highland bamboo sawdust as a stabilizing agent in Jimma City. This study considered two soil samples collected from Jimma City, around the Jimma University Institute of Technology campus and Urael area. The soil samples were mixed-up with the highland bamboo sawdust in proportions of 4%, 8%, 12%, 16%, and 20 %by weight. Tests in lab, such as Atterberg limit, specific gravity, free swell, compaction, California bearing ratio (CBR), and unconfined compressive strength (UCS) were performed for the improvement of subgrade soil. The laboratory tests were performed on mixed soil samples according to the American Association of State Highway and Transportation Officials (AASHTO) and ASTM laboratory test procedures. The designated soil samples were categorized as A-7-5 soil based on the AASHTO and CH based on the Unified Soil Classification System (USCS), which is clay soil with poor engineering characteristics. Tolerable strength was attained with 16%, which is the ideal Highland bamboo sawdust (HBSD) content in improvement of the expansive soil nature. Maximum Dry Density (MDD) improved from 1.45g/cm$^3$ in natural soil to 1.57g/cm$^3$ in 16% HBSD-treated soil. There is a significant change in CBR values from 1.31% to 9.8% with and without highland bamboo sawdust, respectively. Thus, the optimum values were attained at 16% HBSD.

**Keywords:** Engineering properties, expansive soils, experimental, highland bamboo sawdust, optimum ratio

## 1 Introduction

Expansive soils are found in many countries across the world, and their properties make it very challenging to engineers. Expansive soil resists many of the stabilization techniques accessible to engineers because of its strong swelling and shrinkage properties. The phenomenon known as differential heave or settlement happens when expansive soil expands and contracts, leading to significant damage to retaining walls, roads, buildings, and foundations. Therefore, particular thought



Received: 24 November 2024; Received in revised form: 4 May 2025; Accepted: 8 August 2025

is needed when building the structure's foundation on expansive soil [1]. The presence of expansive soils on construction sites is a cause for the failure of geotechnical engineering structures. In South Africa, it is predicted that the annual repair costs for expansive soil damage to buildings will be R100 million. Expansive soil damage in the UK is estimated to cost £400 million a year [2]. Large areas of Ethiopia, primarily in the west, center, and southwest of the nation, are covered in expansive soil. It literally poses a risk to one's finances and lessens the living standard of society. Large sections of freshly planned railway routes, light-duty residential and commercial buildings, projected airfields, and most constructed roadways in the nation are situated in the center of expansive soils. Expanding soil is a major issue in Jimma City, one of the cities in Ethiopia that needs attention to address its effects. Expansive clay is thought to cover more than 40% of Ethiopia, hindering economic development and making building challenging [3]. Near rivers, in locations with high water tables, and areas with limited drainage, this soil is also found locally throughout the nation. Given that many homes are located in areas where landslides are prone, expansive soil in some hilly terrain may cause landslides that risk human life and resources [4].

Increased strength and stability of the soil are achieved through the process of "soil improvement," primarily by mechanical or chemical means. Improved soil gradation, a decrease in plasticity index or swelling potential, and increases in durability and strength are the most frequent benefits of stabilization [5]. In order to increase the geotechnical attributes of poor soils, such as compressibility, strength, permeability, and durability, stabilizing agents (binder materials) are used [6]. Expansive soils can have their engineering qualities greatly improved by mechanical stabilization. The replacement of soil, densification (vibro-flotation), hydraulic alteration via vertical drains, and surcharge loads are some of these techniques [7]. A physical and chemical technique for increasing soil density, reinforcing, cementing, and controlling soil volume for building is called soil stabilization [8, 21].

Applications that require the use of an addition that produces hydrogen sulfide or high carbon content are strictly forbidden. It is well known that these chemicals' emissions harm the environment. Using substances containing heavy metals that could leak and contaminate groundwater is likewise a bad idea. The pH of the soil must be taken into account before applying any stabilizer. Researchers seem to need to conduct geo-environmental assessments according to the additive they are using in order for their researches to be more sustainable [9].

Plant fibers behave differently from traditional synthetic materials by nature, and their ability to operate as reinforcing material is controlled by biochemical features. When compared to other potential fibers, bamboo fiber offers the strongest soil-reinforcing capability and durability based on the compositions of both cellulose and lignin concentration [10]. Bamboo culms have high strength along the axial direction and low strength along the transversal direction of their fibers. The structure of bamboo itself is a composite material consisting of long and aligned cellulose fibers immersed in a ligneous matrix (lignin and hemicellulose) [3]. Sawdust's rough surface provides significant friction, strengthening soil by reducing swelling potential and pressure in samples as more sawdust is added. It has been observed that sawdust by itself, non-cementitious materials, lignin, and cellulose present in sawdust serve as surface active in the interaction soil-water-fiber system, generating a gel of high strength that can contribute to improvements in the strength and compressibility characteristics of the treated soils [11]. More than any other material, bamboo fiber stabilizes soil better and more effectively because to its improved geotechnical qualities, strength it provides to expanding soil, cost-effectiveness, eco-friendliness, and textural roughness that generates friction between the material and soil mix [22]. Bamboo offers a cost-effective, environmentally friendly alternative to commercial resources like cement, fly ash, and lime for soil stabilization, offering practical, financial, and environmental friendly benefits [30-32].

There are several treatment options available (chemical treatment and physical treatment) to increase the durability of bamboo material. Physically, soaking bamboos in hot water, heated air, saturated steam, or UV light for a certain amount of time enhances the durability and strength of the bamboo material; while chemical treatment follows by applying some substances, such as citric acid, copper, arsenic, and chromium to prevent decay for a long time with [29]. Chemical changes that affect how fiber materials interact with soil, such as acetylation, alkali treatment, and permanganate treatment, can improve the characteristics and longevity of the fibers. Blasting, ABS thermoplastics, nano clay, and resins are some other examples of these treatments [3].

The world's arid and semi-arid regions are home to expansive soil deposits, which pose significant challenges to engineering projects due to their propensity to expand during the rainy season and contract during the dry season [14]. Agricultural by-products like rice husk, coconut fibers, sisal, and bamboo play an important role in providing sustainability in minimize energy consumption, conserve non-renewable resources, reduce pollution, and contribute to a healthier environment when eco-friendly materials and products used [18]. The study presented here contributes to the stabilization techniques by assessing the effectiveness of highland bamboo sawdust (HBSD) for improving expansive subgrade soil and determining the effective proportion of HBSD. Laboratory findings and statistical analysis from this study will be used in developing better subgrade soil treatment plans.

## 2 Research Design and Methods

### 2.1 Description of the Study Area

Jimma city is located around 354 kilometers southwest of Addis Ababa. Jimma is located at approximately 7°40′ N latitude and 36°50′ E longitude. These coordinates place Jimma in the southwestern part of the country, within the Oromia Region. Jimma is a significant commercial center, especially known for its coffee production and rich cultural heritage. The town experiences temperature fluctuations between 20 and 30 ℃ and receives 800 to 2500 mm of rainfall on average every year. It is also located between 1718 and 2000 m above sea level. Jimma is primarily covered in red, black, and gray soils. The regular topography with higher elevation and good drainage conditions is where the red-colored soils can be found. The flat geography of the city, with lower altitude and bad drainage conditions, is where the black and gray soils, which encompasses the center and majority of the city, are found [3].

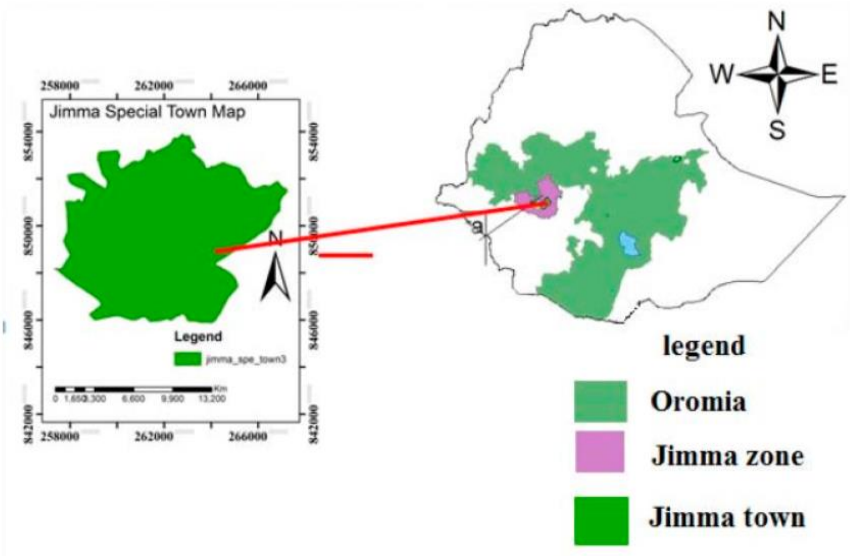


**Fig. 1.** A study area map [4]

### 2.2 Materials

2.2.1 Soil

For this study, two subgrade soils were purposely sampled from Jimma City around the Jimma University Institute of Technology campus (sample 1) and around Urael Sefer (sample 2). The excavation was carried out manually using a shovel. Disturbed and undisturbed samples were collected to investigate the soil properties. The studied soil physical properties are characterized as expansive soil and summarized in **Table 1.**

**Table 1**. Summary of soil physical properties of the study area

| Parameters/Sample name | Sample 1(S1) | Sample 2 (S2) |
|---|---|---|
| Moisture content (%) | 35.3 | 36 |
| Specific gravity (%) | 2.71 | 2.72 |
| Free swell | 110 | 95 |
| Percentage finer #200 (%) | 87.9 | 93.8 |
| Liquid limit (%) | 114.36 | 90 |
| Plastic limit (%) | 44.57 | 42.51 |
| Plasticity index (%) | 69.79 | 47.49 |
| Classification | A-7-5 (18) | A-7-5 (12) |
| MDD (g/cm3) | 1.43 | 1.45 |
| OMC (%) | 26.36 | 24.58 |
| CBR (%) | 1.26 | 1.31 |
| CBR swell | 9.5 | 9.25 |
| UCS (kN/m2) | 51.02 | 68.16 |

The soil physical properties of the study area are characterized as expansive soil and summarized in Table 1. Low plasticity is indicated by a liquid limit which is less than 35 percent, moderate plasticity is between 35 and 50 percent, high plasticity is in the range of 50 and 70 percent, and very high plasticity is in the range of 70 and 90 percent [8]. Hence, these results show that the soils are very high in plastic clay. Accordingly, the soils drop under the A-7-5 soil class based on the AASHTO soil classification system and the CH soil class based on the USCS soil classification system. Soils in this class are generally classified as materials with poor engineering properties that should be used as subgrade materials. Thus, the soil necessitates primary adjustment or enhancements to increase its workability and engineering properties.

2.2.2 Highland Bamboo Sawdust

Bamboo culms have high strength along with axial and low strength along the transversal direction to its fibers. The bamboo structure is a composite material have long and aligned cellulose fibers immersed in a ligneous matrix (lignin and hemicellulose). The primary bamboo chemical constituents are cellulose, lignin, and hemicellulose. The bamboo has about 60% cellulose and 32% lignin matrix. The bamboo fiber covered with lignin is often brittle compared with other natural fibers [15, 16]. Table 2 shows the bamboo sawdust chemical composition adapted from Dessalegn Y. et al. [16].

**Table 2.** Chemical composition of highland bamboo sawdust [16]

| Year | Ash (%) | Extractives (%) | Hemicellulose (%) | Cellulose (%) | Lignin (%) |
|---|---|---|---|---|---|
| One year | 2.57 | 8.78 | 19.14 | 49.36 | 19.38 |
| Two year | 2.09 | 7.65 | 21.6 | 49.57 | 22.27 |
| Three year | 1.19 | 7.54 | 19.61 | 49.99 | 21.12 |

## 2.3 Study Design

A quantitative experimental study was performed to determine the engineering properties of the soil. Field observations, sample collection, literature review, data analysis and interpretation, conclusion, and recommendations were undertaken to classify the engineering properties of the soil. Proceeding to treatment and testing, the sample was prepared in accordance with the methods described in AASHTO and ASTM. Soil and highland bamboo sawdust were then mixed manually to achieve a uniform mix ratio for each test. A series of experiments were performed on the two samples with different percentages of highland bamboo sawdust (0, 4, 8, 12, 16, and 20%), as shown in **Table 3** and **Fig. 3.**

## 2.4 Highland Bamboo Sawdust Preparation

The strength of bamboo increases with age, reaching an optimal strength value between 2.5 and 4 years. After an average of four years, its strength decreases. First the sawdust was allowed to air dry to remove moisture. The bamboo sawdust was then sieved with a 425-micron sieves to remove lumps, gravel, and any extra deleterious particles [17, 18].

As illustrated in **Fig. 2**, the bamboo sawdust passing through different micron sieves was used for various laboratory tests. The highland bamboo sawdust was prepared from fresh bamboo by cutting it into small pieces with axes and then grinding it with a mold and hammer to the desired size for different laboratory tests. Finally, the prepared sawdust was air-dried to remove moisture.

**Fig. 2.** Manually prepared (a) Highland bamboo tree (b) highland bamboo fiber (c) highland bamboo sawdust

### 2.5 Design Mixtures and Sample Designation

**Table 1.** Mixing ratio and sample description

| Sample | Mix Designation | Percentage of highland bamboo sawdust (%) | Percentage of soil (%) |
|---|---|---|---|
| Sample 1 (S1) | Natural soil | 0 | 100 |
| | HBSD4S1 | 4 | 96 |
| | HBSD8S1 | 8 | 92 |
| | HBSD12S1 | 12 | 88 |
| | HBSD16S1 | 16 | 84 |
| | HBSD20S1 | 20 | 80 |
| Sample 2 (S2) | Natural soil | 0 | 100 |
| | HBSD4S2 | 4 | 96 |
| | HBSD8S2 | 8 | 92 |
| | HBSD12S2 | 12 | 88 |
| | HBSD16S2 | 16 | 84 |
| | HBSD20S2 | 20 | 80 |

Expansive subgrade soils can be enhanced by numerous ways. Amongst those approaches, mechanical enhancement is the one being used all over the world. In this study highland bamboo sawdust improvement were used for enhancement of sub grade expansive soils gathered from Jimma City. The study investigated the index properties and strength measurement parameters. The parameters were grain size analysis, specific gravity, natural moisture content, Atterberg limits, compaction, free swell, UCS, CBR and CBR swelling potential of improved expansive clay. There was a variation of those parameters during investigation. The mixture that best satisfies the grading and plasticity requirements is chosen for use in the field after these mixtures have been evaluated. For this study, stabilization was accomplished utilizing 4%, 8%, 12%, 16%, and 20% HBSD of the in weight. Using the plasticity index and the fraction of the finer soils, the ideal amount of bamboo sawdust to be applied to expansive clay soil was calculated. The soil-bamboo sawdust percentage needed for soil stabilization can be assessed using this test procedure.

**Fig. 3.** Sample mixed for laboratory tests

### 2.6 Laboratory Test Program

The soil sample was collected from two distinct sites in Jimma City and brought to a lab for analysis. The expansive soil samples were mixed-up with the highland bamboo sawdust in a 4, 8, 12, 16, and 20% percentage by weight. Laboratory tests such as Atterberg's limit, free swell, compaction, soaked CBR, and UCS were carried out on expansive soil with highland bamboo sawdust for the improvement of subgrade soil. Under this study, AASHTO and ASTM laboratory specifications were used to study the properties of the soil and are presented in **Table 4**.

**Table 2.** Standard testing procedures

| Name of the Tests | AASHTO Standard Procedures | ASTM Standard Procedures |
|---|---|---|
| Moisture content | | D 4318 |
| Specific gravity | | D 854-83 |
| Grain size analysis | | D422-63 |
| Atterberg limits | | D 4318 |
| Modified compaction | | D-1557 |
| California bearing ratio (CBR) | T193-93 | |
| Unconfined compression strength test | | D 2166 |
| Soil classification | | D698-98 |

### 2.7 Estimation of the Optimum Amount of Highland Bamboo Sawdust Ratio

In light of the literature review estimation of the optimum ratio for locally available material using two major methods, the first one was the trial method, and the second one was combining for plasticity index. Estimation of the optimum ratio using this method was assessed based on the plasticity index and percentage finer of the soils [20].

To guarantee adequate mixing, the plasticity index (PI) and liquid limit for fine-grained soils—those with more than 50% of their weight passing through a #200 sieve—must be less than 20 and 40, respectively. The formula below, which specifies the maximum limit of the Plasticity index for choosing materials for soil stabilization, provides a more detailed guideline based on the fines content [23].

$$PI \leq 20 + \left( \frac{50 - \% \, finerthan \, \#200}{4} \right) \quad (1)$$

where, PI = plasticity index

## 3 Results and Discussions

### 3.1 Effect of Highland Bamboo Sawdust on Atterberg Limits

**Table 5** displays the findings of the experiments conducted on soil samples that were natural and soil samples that were combined with varying amounts of highland bamboo sawdust.

**Table 3.** Atterberg limit test result of highland bamboo sawdust expansive soils

| Sample Name | S1 | | | S2 | | |
|---|---|---|---|---|---|---|
| Highland Bamboo Sawdust (%) | (LL) | (PL) | PI | LL | PL | PI |
| 4 | 106.649 | 48.6 | 58.049 | 84.5 | 45.33 | 39.17 |
| 8 | 100 | 50.586 | 49.414 | 80 | 48.25 | 31.75 |
| 12 | 89.53 | 52.30 | 37.23 | 75 | 50.97 | 24.03 |
| 16 | 68.23 | 54.38 | 10.40 | 68 | 52.22 | 8.78 |
| 20 | 62.96 | 57.08 | 5.88 | 60 | 54.94 | 5.06 |

**Note:** LL = Liquid limit; PL = Plastic limit; PI = Plasticity index

For sample 1 (S1) LL decreased from 114.36% at 0% HBSD to 62.96%, and for sample 2, (S2) LL decreased from 90% at 0% HBSD to 60%. Results show that the LL and PI reduced and, the PL improved for all samples. PI decreased from 69.79% at 0% HBSD to 5.88% and 47.49% at 0% HBSD to 5.06% for S1 and S2, respectively. The highest decreases in plastic index happen when it is improved with maximum proportions, and the minimum reductions occur at minimum ratios. The notable decrease in liquid limit and plasticity index shows a sign of improvement. This clearly shows the fact that the plasticity index of treated soil decreased with an increasing quantity of highland bamboo sawdust. The decrease in the plasticity index of the soil with the addition of highland bamboo fiber is due to the high water absorption effect of the fiber, the fiber surface effect, and particle rearrangement of the soil with fiber. Because cellulose fiber has more hydroxyl groups and is therefore more hydrophilic, as well as because of its increased capillary effects, the high fiber content of bamboo sawdust and the micro-cracks found within the fiber contribute to the high water absorption of the bamboo-soil mixture. There is more water absorption when the cellulose concentration rises in conjunction with the number of fiber layers. An increase in the soil's shear strength and a decrease in its plasticity index can result from the soil's bamboo fibers forming a more organized network inside the soil matrix [24].

### 3.2 Effect of Highland Bamboo Sawdust on Free Swell Ratio

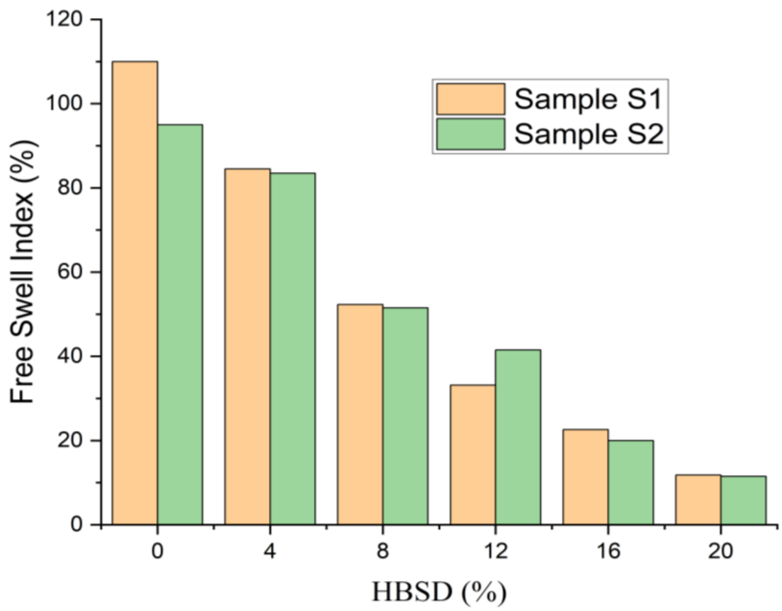


**Fig. 4.** Effect of highland bamboo sawdust on free swell

The free swell test comprises of placing a specified volume of dry soil that passes the No. 40

(425 μm) sieve into a graduated cylinder filled with water and measuring the swelled volume after it has fully settled. The free swell of the improved soil sample is presented in **Fig. 4.**

The effect of free swell from the laboratory test result indicates that the free swell index (FSI) values of the expansive soil have decreased with the increase in the percentage of HBSD, which resulted in a reduction in swelling of the expansive soil. The FSI decreased from 110% in natural soil to 11.8% in treated soil and from 95% in natural soil to 11.5% in treated soil for S1 and S2, respectively. From the test outcomes, it has been noted that the addition of HBSD to expansive soil has resulted in a decrease in the FSI of the soil. The addition of highland bamboo fiber reduces soil free swell due to its high water absorption effect, fiber surface effect, and particle rearrangement [18, 19]. The inclusion of bamboo fiber increases the tensile strength of the soil, reducing its ductility. Additionally, the soil matrix's pore space is altered, contributing to the reduction in the free swell index of expansive soil [11].

### 3.3 Effect of Highland Bamboo Sawdust on Moisture-Density Relationship

The moisture-density relationship was determined using a modified proctor compaction test according to ASTM D-1557. The optimum moisture content and maximum dry density of improved soils are presented in **Fig. 5**.

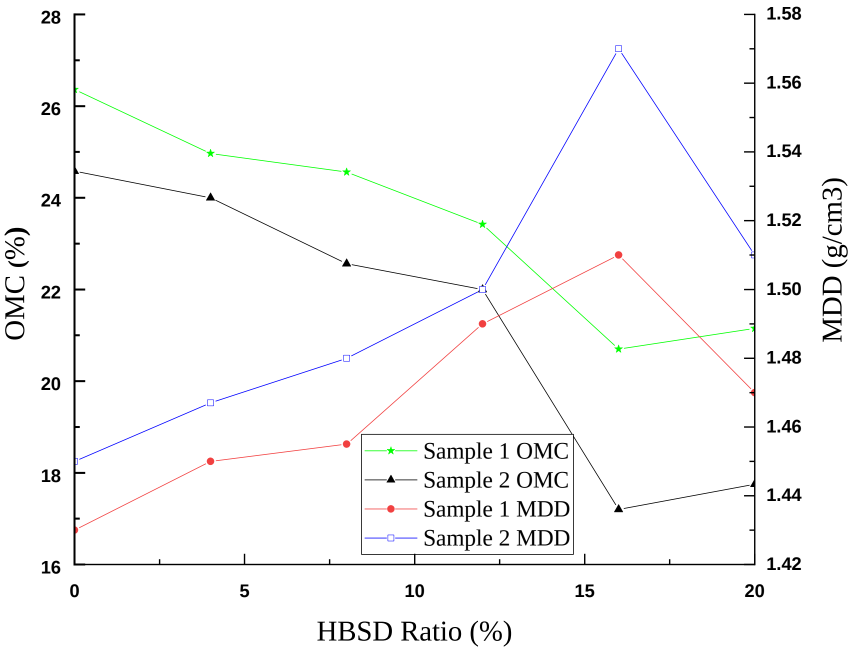


**Fig. 5.** Effect of HBSD to expansive soil on OMC and MDD for sample 1 and sample 2

The experiment conducted on expansive soil mixed with highland bamboo sawdust (HBSD) yielded significant changes in both maximum dry density (MDD) and optimum moisture content (OMC). Across all cases, the OMC decreased while the MDD increased up to the optimum level with the addition of varying percentages of HBSD. Specifically, the maximum dry density increased from 1.43 g/cm$^3$ to 1.51 g/cm$^3$ for S1 and from 1.45 g/cm$^3$ to 1.57 g/cm$^3$ for S2 when HBSD content reached 16%. Conversely, the optimum moisture content decreased from 26.361% to 20.7% for S1 and from 24.58% to 17.2% for S2 at the same HBSD content level. The increase in MDD and decrease in OMC can be attributed to the hydrophilic nature of HBSD, which reduces water absorption by clay minerals in the soil upon mixing. This leads to a denser packing of soil particles, hence increasing MDD and decreasing OMC. However, beyond the optimum percentage of HBSD, the dry density starts to decrease due to the lightweight and hydrophilic nature of the fiber, which prevents efficient particle packing. Excess sawdust can disrupt soil structure, hindering effective particle packing and resulting in decreased density.

In summary, the addition of HBSD to expansive soil positively affects its engineering properties up to a certain percentage, enhancing MDD and reducing OMC. Beyond this optimum percentage, however, the effectiveness diminishes, leading to decreased dry density due to particle interference and inefficient particle packing caused by surplus sawdust. Bamboo sawdust can absorb water and allow for a more compact arrangement of particles, it reduces voids between soil particles, resulting in a denser packing of the soil-sawdust mixture. This is why the maximum dry density (MDD) increases as more bamboo sawdust is added to the expansive soil [25]. Moreover, particle interference a surplus of sawdust can upset the soil's structure, preventing the efficient packing of soil particles and resulting in a decrease in density is the reason for the decrease in maximum dry density (MDD) that occurs after the ideal percentage of bamboo sawdust has been reached [26].

### 3.4 Effect of Highland Bamboo Sawdust on CBR Value Result

This CBR test was performed as per AASHTO standard procedure T193-93. The soils improved by highland bamboo sawdust displayed an improvement in strength. CBR is one of the parameters used to measure strength. The test results for improved and natural subgrades are shown in **Fig. 6.**

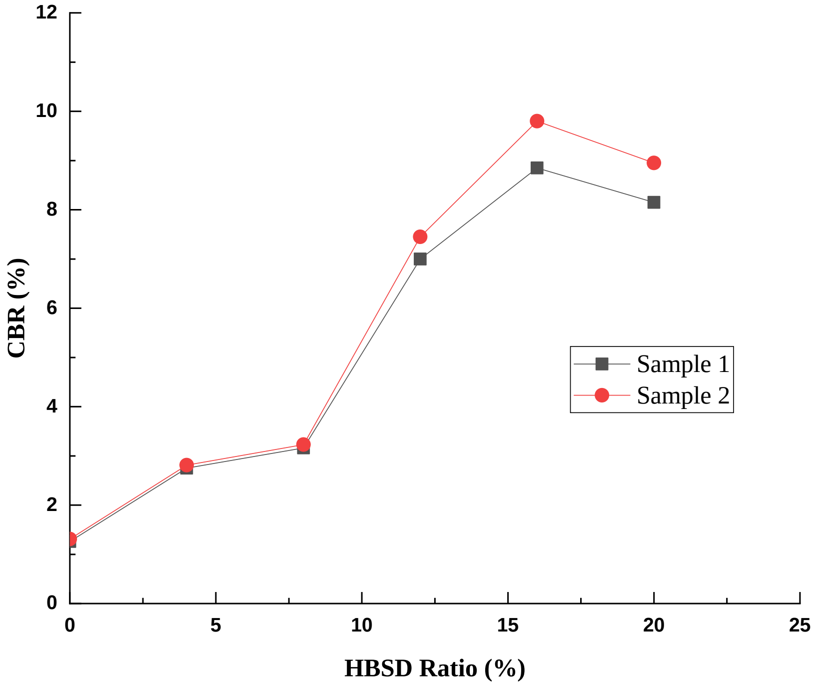


**Fig. 6.** Effects of HBSD on CBR value

**Table 4.** The overall relationship amongst CBR values and the quality of the subgrade soils [21]

| CBR-Values | Quality of Subgrade |
|---|---|
| 0-3% | Very Poor Subgrade |
| 3-7% | Poor to Fair Subgrade |
| 7-20% | Fair Subgrade |
| 20-50% | Good Subgrade |
| >50% | Excellent Subgrade |

The CBR values of the natural subgrade soils in the two samples did not satisfy the condition of subgrade soils based on the ERA criteria (CBR > 5%). CBR increased with increased highland bamboo sawdust proportions up to the optimum amount of 16%, and then the CBR value decreased. By the same ratio, the improvement of sample 2 is greater than that of sample 1 using highland bamboo sawdust. The improvement done at the optimum ratio fulfills both the AACRA and ERA criteria (CBR > 5%) for subgrade.

Hence, the natural soils were discovered to be highly plastic expansive clay with poor bearing capacity when soaked and have high swelling potential, falling below the standard recommendations for the majority of geotechnical construction projects, particularly highway construction. To use CBR values less than 3% would be inappropriate from both a practical and financial perspective, as it would normally be unsuitable to lay civil structures, especially pavement, on soils of such low bearing capacity. CBR values at 95% MDD increased from 1.26% natural soil to 8.85% treated soil and 1.31% to 9.8% treated soil at 16% of HBSD content for S1 and S2, respectively. The maximum values of CBR were 8.85% and 9.8% for S1 and S2, respectively. The improved soil using highland bamboo sawdust was very suitable for subgrade soils. It raises the CBR values of samples 1 and 2 from very poor to fair, as shown in **Table 6**. The increase in CBR value is due to the interlock or interconnection between the soil and the highland bamboo fiber. The application of forces and loads in tests enhances soil behavior by tightening grains and reducing voids, thereby improving the overall quality of the soil. [13,18].

### 3.5 Effect of Highland Bamboo Sawdust on CBR Swell

A substantial improvement in the soil's CBR value, an indication of increased strength, is achieved by using bamboo fiber in the stabilization process. According to the outcome, expanding soil qualities may be significantly improved by using bamboo sawdust [27].

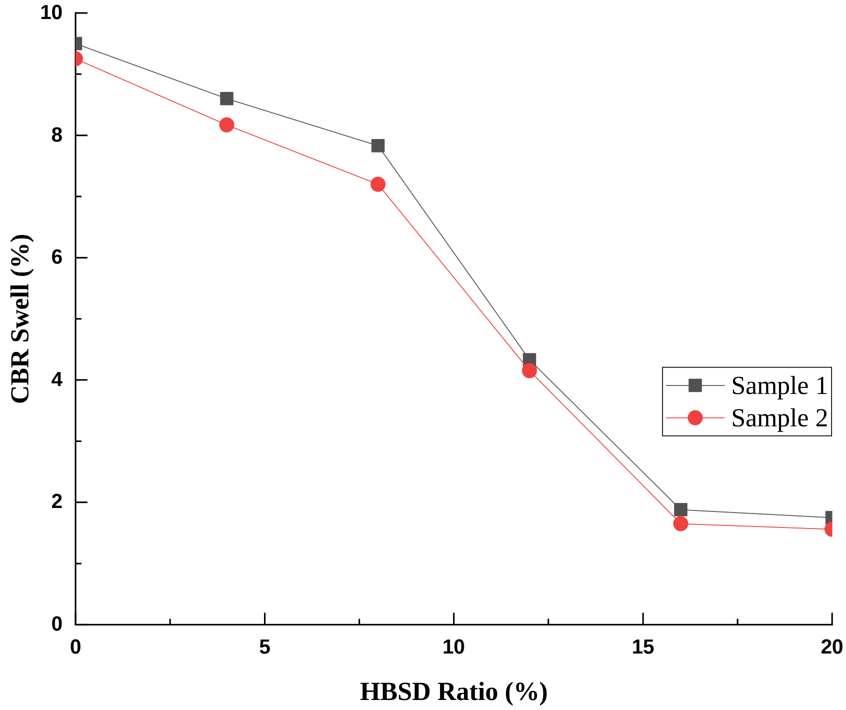


**Fig. 7.** Effects of Highland Bamboo Sawdust on CBR Swell

The effect of HBSD on the CBR swells for the soil-HBSD mixtures is shown in **Fig. 7**. The result shows a decrease in the CBR swell from 9.5% to 1.75% for S1 and 9.25% to 1.56% for S2 with the addition of 20% highland bamboo sawdust. So, the minimum CBR swell value with the maximum ratio is highland bamboo sawdust. The ERA Manual recommends that sub-grade soil should have a CBR swell of less than 2 percent, so the improved soil should satisfy this standard, and it is possible to use the improved soil as sub-grade material in highway construction [20].

### 3.6 Effect of Highland Bamboo Sawdust on UCS Values

The samples were combined and compacted at maximum dry density and optimum moisture content, and the tests were performed on remolded, untreated specimens and remolded specimens treated with varying percentages of highland bamboo sawdust contents. **Fig. 8** shows the laboratory test results of the unconfined compression test for expansive soils, which improved a varying percentage of highland bamboo sawdust.

As shown in **Fig. 8**, the unconfined compressive strength of the remolded soils without the addition of highland bamboo sawdust is 51.024 kN/m$^2$ for S1 and 68.155 kN/m$^2$ for S2. This shows that the soils are very soft and low in strength, but the addition of highland bamboo sawdust gave the radically highest strength value at 16% of the highland bamboo sawdust content for the two samples. The increase in the UCS is attributed to the roughness of the highland bamboo sawdust, which produces large friction between the soil particles, and by nature, highland bamboo has a high compression resistance capacity. The sawdust particles might work as filler in the void spaces between the particles. However, as the sawdust content increases above 16%, the sawdust particles start replacing the clay particles in such a way that it reduces the cohesion between the clay particles. As the highland bamboo sawdust, the large volume of highland bamboo sawdust in the soil mix (sawdust-sawdust interaction) may influence content increases of up to 16% UCS values and start replacing the clay particles, changing the behavior of the highland bamboo sawdust-soil matrix. Hence, 16% of highland bamboo sawdust shows maximum improvement in expansive soil and changes the soil from very soft to high (firm) consistency. Due to the rearrangement and new texture brought about by the fibers' entry into the soil matrix, the soil's unconfined compressive strength has changed [18].

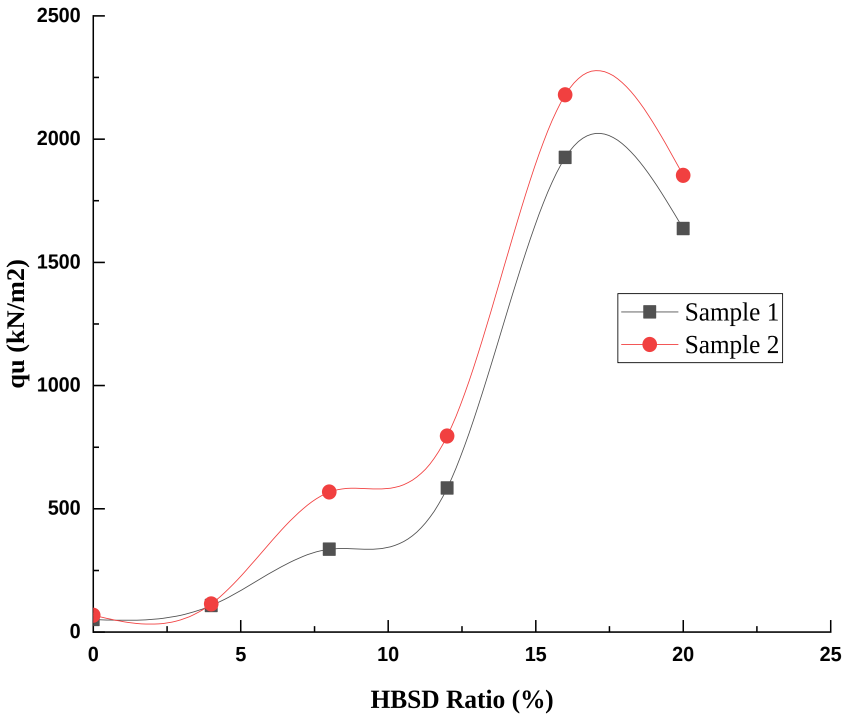


**Fig. 8.** Effects of HBSD on unconfined compression strength

### 3.7 Estimated Optimum Amount of Highland Bamboo Sawdust Ratio

The result of adding highland bamboo sawdust to expansive soil is to change the properties of expansive soil. Adding highland bamboo sawdust to expansive soil leads to drastic adjustments in laboratory tests of the Atterberg limit, compaction characteristic, CBR, and unconfined compression strength. In the compaction characteristic, when the highland bamboo sawdust is added to expansive soil, it decreases the moisture content and, inversely, increases the maximum density. This shows that adding highland bamboo sawdust can improve the compaction characteristics of MDD and OMC. Farther more, the addition of highland bamboo sawdust to the expansive soil increases the CBR value and, inversely, decreases the swelling potential of the expansive soil. The laboratory values of CBR increased from 1.26% in natural soil to 8.85% for S1 and 1.31% in natural soil to 9.8% for S2 at 16% highland bamboo sawdust. This indicates that adding HBSD to expansive soil can change the characteristics of expansive soil, which results in an expansive subgrade. Therefore, the addition of high HBSD to expansive soil resulted in a decrease in free swell, OMC, LL, PI, and CBR swell. Conversely, the addition of HBSD to expansive soil increases the value of PL, MDD, CBR, and UCS.

This indicates that the effect of adding highland bamboo sawdust to expansive soil changes the properties of expansive soil and increases its strength. Therefore, the addition of highland bamboo sawdust to expansive soil improves the geotechnical properties of expansive soil.

The value of MDD, UCS, and CBR decreased after 16%; this indicates that the optimum percentage required to achieve the study is 16%. Generally, adding highland bamboo sawdust to expansive soil can have effects on the laboratory test of soil. Hence, the results indicate that adding highland bamboo sawdust to expansive soil is important in terms of obtaining strength and cost. The optimum HBSD percentage of highland bamboo sawdust is reached at 16%, indicating that the necessary strength has been attained.

The observed increases in dry density, specific gravity, CBR value, and UCS all reach the optimal ratio of HBSW. This suggests that the sawdust's chemical composition causes interference with the adsorbed water in the clay structure, leading to greater specific gravity and other parameters like as dry density. However, the repelling effect between the clay layers stops the properties, such as specific gravity and dry density, from increasing beyond the ideal ratio of 16%. This indicates that the behavior of the soil starts to shift from semi-buoyant to buoyant, which results in a decrease in specific gravity and dry density [28].

From grain size analysis, the percentage finer than 0.075mm sieve was 87.9% for sample 1 and 93.8% for sample 2. Substituting the percentage of finer than 0.075mm in equation (1), determine the optimum used to improve the expansive clay.

$$PI = 20 + \left( \frac{50 - 87.9}{4} \right) = 10.53 \quad (2)$$

$$PI\left(2\right) = 20 + \left( \frac{50 - 93.8}{4} \right) = 9.05 \quad (3)$$

where, $PI(1)$ = computed plasticity index value of sample 1; $PI(2)$ = computed plasticity index value of sample 2

For this study, the plasticity index of improved soils was less than the computed plasticity index at 16% of HBSD. Therefore, the optimum HBSD ratio of the soils considered for this study was 16% of HBSD by weight.

## 4 Conclusions

The laboratory tests performed for this study were moisture content, specific gravity, grain size analysis, Atterberg limits, modified proctor test, free swell test, unconfined compression strength test, California Bearing Ratio, and CBR swell tests. The test procedures were followed as per AASHTO and ASTM laboratory test standards. The improvements were done using 4, 8, 12, 16, and 20% of highland bamboo sawdust by weight. The addition of HBSD improved the unconfined compressive strength of the weak soils.

The maximum value of unconfined compressive strength was at 16% HBSD content, and the unconfined compressive strength reduced when the HBSD content increased beyond the optimum contents. Appropriate strength was achieved at 16%, which is the optimum Highland bamboo sawdust (HBSD) for improving the engineering properties of the expansive soils that fulfill Ethiopian Road Authority (ERA) requirements. The use of 16% HBSD reduces the CBR swell from 9.5% to 1.88% for S1 and 9.25% to 1.65% for S2.

Generally, the use of highland bamboo sawdust for expansive soil improvement highly increases the PL, MDD, CBR, and UCS and decreases the FS, LL, PI, OMC, and CBR swells of the expansive soil sample. Because of its enhanced geotechnical qualities, strength, affordability, environmental friendliness, and textural roughness—which creates friction with the soil mixture—bamboo fiber is better at stabilizing soil.

This research could potentially provide valuable insights into optimizing the use of highland bamboo sawdust for expansive soil improvement. By exploring different reinforcing patterns, orientations, sizes, and stiffness of bamboo, a more comprehensive understanding of its impact on stabilizing expansive subgrade soil can be achieved. Such knowledge can contribute to the development of more effective and sustainable geotechnical solutions for expansive soil stabilization in the future.

In general, the subgrade soils considered for this study exhibited very low load-bearing capacity and high compressibility, rendering them unsuitable for highway and building foundation applications without improvement. Therefore, the use of HBSD should be considered as a viable method for soil stabilization, particularly in regions with expansive soils. This approach not only enhances the load-bearing capacity and reduces the compressibility of the soil but also contributes to more sustainable and cost-effective construction practices by utilizing natural and locally available materials.

## Acknowledgement

The authors are pleased to acknowledge the Jimma Institute of Technology for granting permission and providing laboratory services necessary for the accomplishment of this study.

## Funding Statement

The authors received no specific funding for this study.

## CRediT authorship contribution statement

**Sintayehu Begashaw**: Conceptualization, Investigation, Data Curation, Formal analysis, Writing – original draft. **Alemineh Sorsa**: Conceptualization, Supervision, Investigation, Methodology, Data Curation, Formal analysis, writing—review & editing. **Chemeda Alemu**: Supervision, Investigation, Data Curation, Formal Analysis, Writing – review & editing.

## Conflicts of Interest

The authors declare no conflict of interest.

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