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Using readily available natural fibers to reinforce the expansive subgrade soil through analytical and experimental studies

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Article

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Abstract

Expansive soils cause considerable challenges in road construction due to their volumetric changes, which can lead to pavement deterioration. Although conventional soil stabilizers are effective, they are too expensive and not environmentally friendly. This study examines the use of locally available teff and enset natural fibers, which are derived from the enset and teff plants, as sustainable alternatives for reinforcing expansive soil obtained from Wolaita, Ethiopia. The variations of the teff and enset fibers used in this study are 0.25; 0.5; 0.75 & 1%. The untreated soil displayed a Maximum Dry Density (*MDD*) of 1.429 gm/cm^3, Optimum Moisture Content (*OMC*) of 25.71%, California Bearing Ratio (*CBR*) of 2.85%, and an Unconfined Compressive Strength (*UCS*) of 36.5 kilopascals. The incorporation of these fibers led to significant enhancements in these properties, with an increase of 4.4% in dry density, 163.2% in *CBR*, and 352% in compressive strength. Moreover, notable reductions in moisture content, plasticity index (*PI*), free swelling, and linear shrinkage were recorded, resulting in maximum decrease of 22.6%, 8.6%, 78.3%, and 81.2%, respectively. Optimal performance was achieved by adding 0.75% of each fiber type to the soil, cut to a length of 20 mm, which was compacted at its *MDD* and *OMC*. These findings suggest that such locally available natural fiber reinforcement can be a cost-effective and environment friendly solution for improving the engineering properties of expansive soils that can be judiciously utilized in road construction. Statistical models were developed to predict the *CBR* value based on other index properties of the soil showing close agreement with experimental findings.

1. Introduction

Expansive soils, which are common in Ethiopia, experience substantial change in volume due to variation in moisture content leading to swelling and shrinkage and damaging infrastructures. By employing specialized techniques and materials, engineers can minimize these impacts, ensuring that the structures remain stable and safe over time.

Building a structure on expansive soil often results heaving depression, cracking, and soil swelling (Adem & Vanapalli, 2015; Chala et al., 2020; Wang et al., 2020; Al-Kalili et al., 2022). The high clay content in this soil absorbs and retains water resulting in swelling in rainy season and when dries results to depression and bumpy surface. One recommended technique for improving soil characteristics is chemical stabilization, but this method is too expensive and may have negative environmental impacts. A more sustainable solution involves treating expansive soils with locally available natural materials, which can effectively enhance soil performance in an eco-friendly manner.

Using locally sourced materials reduces transportation costs and carbon emissions, environment friendly, sustainable, and normally compatible with the existing soil. This approach not only supports local economies but also promotes biodiversity and helps preserve the natural landscape (Prabakar & Sridhar, 2002; Anagnostopoulos et al., 2013; Maniyazawal, 2020; Feleke & Tekalign, 2022). The processes involved in soil treatment help achieve the properties required for construction work (Nwachukwu & Eburukevwe, 2013; Mahedi et al., 2020).

Soil stabilization is the process of enhancing soil properties by mixing in reinforcing materials accomplished through biological, chemical, physical, mechanical, or a combination of these techniques, enabling adjustments to the soil's natural characteristics to fulfill the required technical specifications. The primary objective of soil stabilization is to improve the soil's strength, durability, and load-bearing

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capacity, thereby making it suitable for construction and various engineering applications (Correia et al., 2015; Khan et al., 2021). Using readily available and reproducible fiber materials for soil reinforcement is considered an effective method for improving ground conditions (Ghavami et al., 1999; Ali, 2011; Torgal & Jalali, 2011).

Natural fibers, such as jute found in marshy or waterlogged areas, can enhance various weak soils, including black cotton soil, organic soils, peats, and clays (Hossain et al., 2015; Dang et al., 2016). Jute fibers on one hand increases the *CBR* value of problematic soils, increasing the soil reinforcement, and offering a cost-effective solution, but on the other hand the availability and eco-friendliness still remain questionable in countries like Ethiopia.

The potential advantages of using palm fiber (1%) can reinforce expansive soil, enhancing the *CBR*, but it is time-consuming to obtain accurate results, and increasing the fiber content can lead to higher costs. Similarly, the beneficial effects of incorporating barley straw fiber, particularly in reducing shrinkage, shortening curing time, and improving compressive strength cannot be ruled out, but the availability and cost are the major hurdle.

The stabilization of expansive soil using various admixtures and natural fibers can improve the soil's strength, bearing capacity, and durability, reducing permeability and water absorption (Chauhan et al., 2008; Hejazi et al., 2012). Moreover, excavating and transporting materials from distant borrow pits to construction sites create both economic and environmental concerns. Therefore, treating expansive soil in situ emerges as a practical solution to these problems (Afrin, 2017; Firoozi et al., 2017; Bekkouche et al., 2022).

According to Ashour et al. (2010) the study aimed to demonstrate how reinforcing natural fibers like wheat straw, barley straw and wood can be used to create over-plaster material consisting of cohesive soil and sand. The only issue is their cost of purchase and availability.

According to Cao et al. (2019), the reinforcement of expansive soil by basalt fiber in combination of cement and fly ash enhances the mechanical properties and microstructure of cement-fly ash-stabilized soil. Adding basalt fibers significantly enhances *UCS*, dynamic compressive strength, and energy absorption capacity. The optimal content of basalt fibers was determined is 0.6%, where the improvements in these properties peaked before declining at higher concentrations. Basalt fibers also change the failure patterns of stabilized soil by reducing the fractal dimension of broken fragments as the fiber content increases, shift towards more ductile failure modes. At the optimal 0.6% fiber content, the soil achieves a stable internal structure with effective bonding between the fibers and the soil. However, just doubling the fiber content, weak interfaces between fibers affect the mechanical properties. Under impact loading, dynamic increase factors and specific energy absorption exhibited similar trends, showing initial improvements followed by a decline at higher fiber contents. Hence, basalt fibers not only enhance static and dynamic mechanical properties but also influence the microstructure of the material up to a certain threshold beyond which fiber interactions may become detrimental.

According to Birmeta et al. (2004) and Dessalegn (2019), using natural fibers such as enset and teff improve soil quality. These fibers are cost-effective, readily available, biodegradable, and environment friendly. In this study, expansive soil was collected and subjected to various laboratory tests to evaluate its engineering properties. The research also examined the impact of incorporating enset and teff fibers of different lengths and proportions to reinforce the soil and mitigate its expansive nature. These agricultural biproducts provide a sustainable and affordable solution for improving expansive clay soils. These fibers have high specific gravity and tensile strength, making them effective in reducing soil expansion. Moreover, their agricultural origin enhances their cost-effectiveness and eco-friendliness for construction applications. The study demonstrates that enset ventricosum and teff straw fibers can be combined with other materials and local soil to stabilize the subgrade, sub-base, and embankment for roads.

2. Materials and methods

2.1 Location of study area

The city of Wolaita Soddo is located in south-central Ethiopia, has a latitude and longitude of 6°54' N 37°45' E, and an altitude ranging from 1,600 to 2,100 meters above sea level (Figure 1).

The Methodology adopted in this study is shown in Figure 2.

2.1.1 Methods of data collection

The research utilized both primary and secondary data. Primary data was collected from test pits selected along the road project area, while the secondary data was obtained from the road project along Wolaita Soddo to Omo River. Additionally, essential secondary data for this study were also collected from various government and non-government organizations. Local natural fibers (such as enset fiber and teff straw) were purchased from the local market at a nominal cost. These experimental works are used for pavement design.

2.1.2 Expansive soil

The expansive soil sample used in this study was collected from Wolaita Soddo area of southern Ethiopia. The soil is grayish black in color consisting of highly plastic clay. According to the Unified Soil Classification System (USCS), this soil is categorized as CH. The general characteristic of expansive soil is classified in Table 1 and the details of the physical properties of the untreated soil are presented in Table 2.

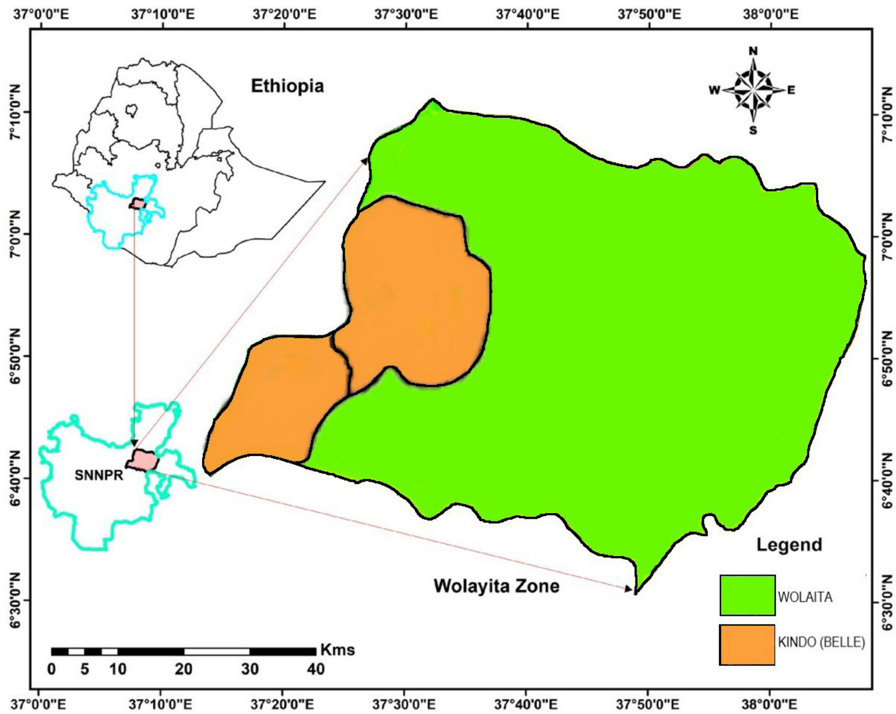

Figure 1. Map of the study area.

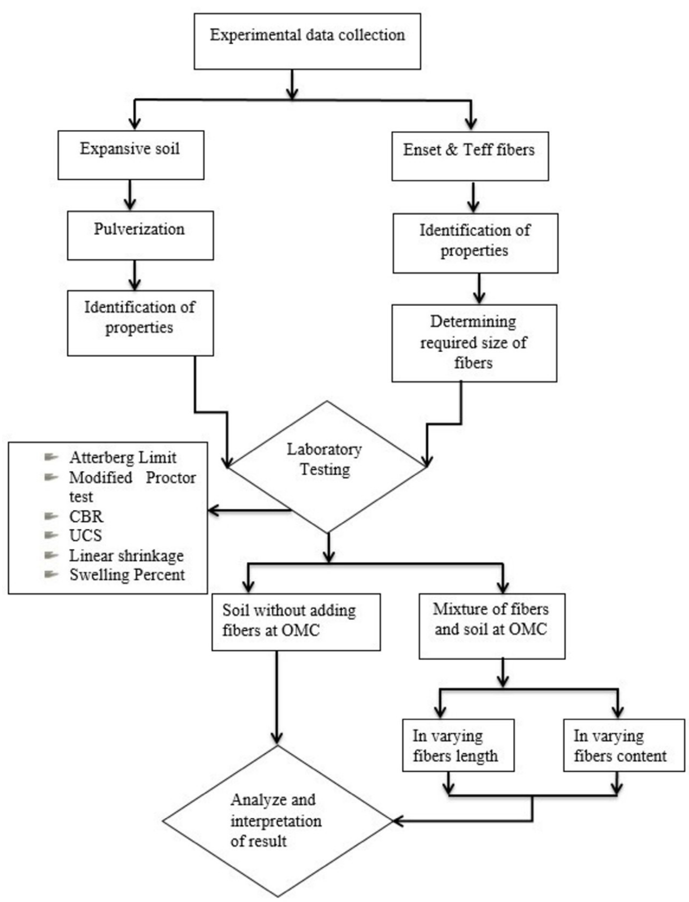

Figure 2. Flow chart of the adopted methodology.

Figure 3. Collection of locally available enset fiber.

Table 1. Degree of expansion of the soil.

% passing #200 sieve	Liquid Limit (*LL*) (%)	Standard penetration resistance (blows/ft)	Total volume change (%)	Degree of expansion
<95	>60	>30	>10	Very high
60-95	20-30	20-30	3-10	High
30-60	30-40	10-20	1-5	Medium
<30	<30	<10	<1	Low

2.1.3 Enset ventricosum fiber

Enset is primarily cultivated within its native indigenous farming systems in South and Southwestern Ethiopia (Figure 3). However, it has gained significant attention across the country due to its remarkable medicinal properties and drought resistance (Kunyanga et al., 2012; Dessalegn, 2019). This plant also serves as a major source of fiber known as "kacha," which the local people use to create ropes and mats. The density of the enset fiber is 690 g/cm^3, indicating a light density and its snap force is measured at 15.4 N, demonstrating strong tensile strength. The fiber density is obtained by using Liquid Displacement method. Snap force is an economical and efficient method for joining two different components, defined as the difference between the actual force applied and the touch force observed in laboratory results.

Four different lengths of fibers (10 mm, 15 mm, 20 mm, and 25 mm) were tested to improve the problematic local soil. 20 mm length showed the best results when mixed with expansive soil. Therefore, for this study, the 20 mm length was selected. The characteristics and components of the enset fiber are illustrated in Table 3.

Due to its low water absorbability, high tensile strength, UV protectiveness, and non-decomposability, this fiber is more suitable for use.

Table 2. Physical properties of untreated soil of the study area.

Soil properties	Values
Specific gravity	2.60
Liquid limit (%) (as per AASHTO T-90-96)	75.50
Plastic limit (%) (as per AASHTO T-90-96)	33.00
Plastic index (%) (as per AASHTO T-90-96)	42.50
USCS	CH
CBR (%) (as per AASHTO T-90-96)	2.70
MDD (kg/cm^3)	1.43
OMC (%)	25.70
Shrinkage limit (%)	11.61
Free swelling (%) (as per IS-2720) = $(V_f - V_i)/V_i$	85.00

Where, V_f = volume of soil after 24hr soaking, V_i = initial volume of soil before soaking

2.2 Sample preparation and test procedures

For the laboratory work, the soil sample was prepared following the method as per AASHTO T87-86 (2000). The sample was air-dried for two days and then pulverized using a rubber-covered Muller. This process aimed to break up the aggregation of soil particles without reducing the size of the individual grains. To ensure a uniformly classified representative sample for various tests, the soil sample was quartered using a splitter.

Table 3. Characterization of organic components of the enset fiber (Esayas et al., 2018).

Fiber properties	Test result	Implication
Cellulose (%)	62.00	Complex carbohydrate
Hemi cellulose	19.00	
Moisture content (%)	15.47	Absorbent
Lignin (%)	5.00	UV protective and non-decomposable

To conduct the Atterberg and free swell tests, the sample was prepared using a # 40 sieve (0.425 mm). For compaction, *CBR* and *UC*S tests, the sample was prepared using a # 4 sieve (4.75 mm), while a #10 sieve (2.00 mm) was used for specific gravity tests.

The representative sampling technique was applied by selecting specific parameters to ensure certain characteristics for this research study, which typically focuses on particular geotechnical properties. The sample size for the research was determined according to the AASHTO T88 standard.

The proportions of enset ventricosum and teff straw fibers used for treating expansive soil were 0.25%, 0.5%, 0.75%, and 1.0%. For each mixture, the weight of individual material was calculated based on the *OMC* and *MDD* obtained from the modified Proctor compaction test, as specified in AASHTO T180. Both fibers are dried by the sunlight.

The modified Proctor Test is a laboratory method used to determine the *OMC* and *MDD* of soil. In this process, soil was mixed with enset ventricosum and teff straw fibers in a dry state until the mixture becomes uniform. Water was then gradually added to achieve a consistent texture. The weight of each specimen was calculated based on its volume and the *MDD* obtained from compaction tests. This weight was divided into five equal portions, with each portion compacted in 25 mm layers within an iron mold. The specimens were subsequently placed in plastic bags to prevent evaporation, maintaining a temperature of approximately 25 °C for 7, 14, and 28 days.

Finally, the index properties of the treated soil were examined, and a regression model was developed to predict the *CBR* value using the index properties determined in the laboratory.

3. Results and discussions

Experimental lab test results for various percentages of enset ventricosum & teff straw fibers and a combination of them are described as follows:

3.1 Sample preparation and test procedures

Compaction testing was carried out using the AASHTO T 180-95 (Modified Proctor Test) standard. This evaluated the influence of natural fibers on the compaction characteristics of expansive soil. The study incorporated Enset ventricosum fibers and Teff straw fibers, both individually and blended, at varying proportions. Fiber-reinforced soil samples were prepared and then tested using the modified Proctor compaction method. The outcomes are shown in Figures 4–6 of the manuscript.

The results showed that increasing the content of both Enset ventricosum and Teff straw fibers led to higher maximum dry density (*MDD*) and lower optimum moisture content (*OMC*) up to a certain point. This suggests that moderate fiber addition improved soil particle packing and densification. However, when fiber content exceeded approximately 1%, *MDD* decreased and *OMC* increased. This change indicates that excessive fiber content created more voids and increased water absorption, which reduced compaction efficiency and dry density.

The graph presented in Figure 4 indicates that adding enset fiber to natural soil increases the dry density, until the optimum fiber percentage of 0.75%. Beyond this percentage, it shows a decrease in dry density.

The data shown in Figure 6 indicates that adding teff fiber to natural soil, increases the dry density up to the optimum fiber percentage of 0.75%, beyond which it shows a reverse effect.

The combined mixture of teff and insect fiber along with natural soil data indicated effective reinforcement of the soil. This resulted in a significant improvement in dry density due to the proper interlock between the particles.

3.2 Strength characteristics

3.2.1 California bearing ratio test results and descriptions

According to AASHTO T-193, 250 g soil sample was prepared for the laboratory testing. The specified fiber content ranged from 0.25% to 1%, and both types of fibers were incorporated into the samples. The samples were mixed in the specified proportions along with the appropriate amount of water. The modified Proctor test method was utilized, which involves compacting the entire soil sample into five layers, applying evenly distributed blows on each layer with a 4.6 kg rammer dropped from a height of 450 mm. The testing process was conducted in three stages: molding, soaking for 96 hours, and penetration testing.

The analysis of *CBR* test data for untreated soil and soil treated with a combination of teff and enset fibers is presented in Figure 7. The *CB*R value of soil stabilized with teff fiber exhibited only a slight change when added to the soil. However, the test results for the mixture of teff and enset fibers were significantly better compared to those for the soil stabilized with either teff or enset fiber alone. The experiment indicated that as the percentage of teff and enset fibers increased up to the optimum content, the *CBR* value also improved. The maximum *CBR* values obtained were 72% for teff fiber, 89.5% for enset fiber, and an impressive 342.1% for the combination of both, compared to just 2.85% for untreated soil. This suggests that the synergistic effect of

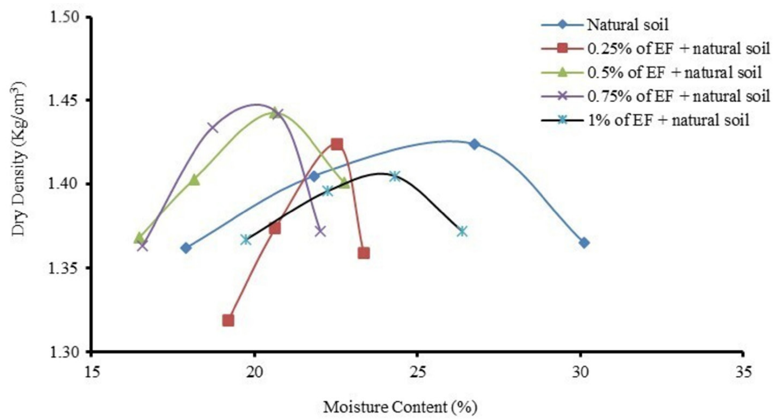

Figure 4. Compaction characteristics of soil stabilized with 0.25 to 0.75% EF.

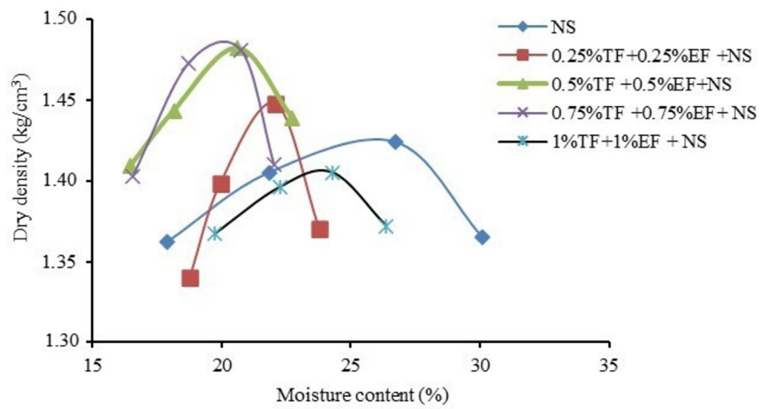

Figure 6. Compaction characteristics of soil stabilized with 0.25 to 1% of teff and enset fiber mixture.

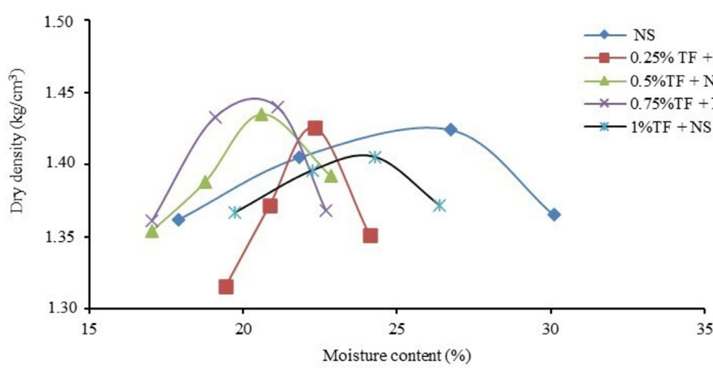

Figure 5. Compaction characteristics of soil stabilized with 0.25 to 1% of teff fiber.

the two fibers at their optimal proportions is greater than when they are used individually, while recognizing that both fibers still have positive impacts when used on their own.

The data presented in Figure 7 indicates that the combination of teff and enset fiber significantly improves *CBR*. Specifically, adding teff and enset fiber amounts ranging from 0.25% to 0.75% enhances the performance of natural soil, while additions greater than 0.75% have a negative impact. Based on the laboratory results, the *CBR* values obtained are crucial for designing pavements suitable for both low and high-traffic conditions. The characteristics of physical properties of native and reinforced soil are described in Table 4.

3.2.2 Characteristics of unconfined compression strength

Three hundred samples have a minimum diameter of 30 mm were used for the *UCS* test as per AASHTO T 208-92. It is evident that soil treated with a mixture of teff and enset fibers demonstrates a significant increase in *UCS* (Figure 8). The graph shows that as the proportion of teff and enset fibers in the mixture increases, the *UCS* also rises, reaching to an optimum proportion. The *UCS* value increases from 36.5 kPa to 242.8 kPa. This data indicates that the *UCS* of soil treated with enset and teff fibers increased by 565.2% compared to that of untreated soil.

3.3 Atterberg's limit test results and interpretations

Table 4 displays the results of Atterberg limits tests conducted on soil samples treated with various proportions of enset and teff fibers. These tests evaluate changes in soil plasticity, focusing specifically on the *LL*, *PL*, and *PI* when these fibers are used as reinforcement. The data indicates that adding enset fiber to mixtures of teff fiber and native soil has a limited impact on overall soil plasticity. However, this effect becomes more pronounced at specific fiber content levels. Notably, when a total of 0.75% enset and teff fiber is incorporated into the soil matrix, the plasticity index significantly decreases, reaching approximately 46% of its original value. This reduction in plasticity indicates improved soil stability, as it lowers the soil's tendency to deform under load or change due to environmental moisture. Such modifications in soil properties can be advantageous for geotechnical applications that require improved soil performance.

3.4 Development of linear regression model

A linear regression model was developed to compare observed and predicted values. Both single and multiple linear regression analyses were utilized. The single linear regression analysis identified the relationship between dependent and independent variables to determine the best fit line. In contrast, multiple linear regressions were employed to establish the regression equation comparing the observed and predicted values.

The primary aim of this model is to characterize the strength of sub-grade soil using statistical analysis of soil index parameters. The influence of one variable on another was assessed using the linear regression method in SPSS software. Following the experimental work, the next step was to develop a statistical model to estimate the *CBR* value by considering the engineering properties of the soil. This approach is important because determining the

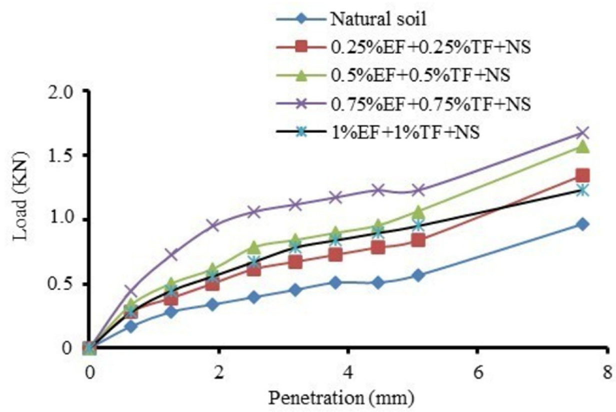

Figure 7. *CBR* value of untreated soil treated with the mixture of 0.25 to 1% of teff ash and enset fiber.

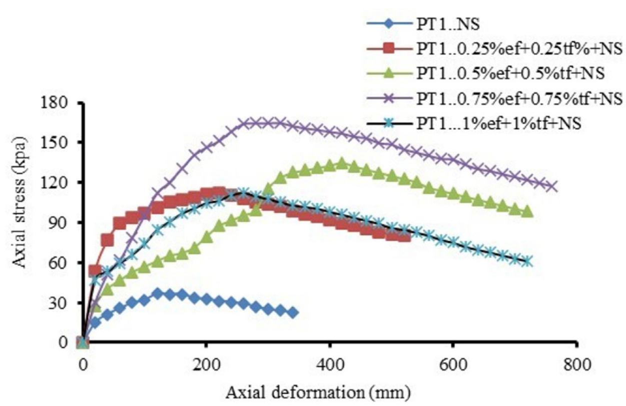

Figure 8. The *UCS* curves for various proportion of enset and teff fiber.

Table 4. Characteristics of physical properties of native and reinforced soil of study area.

Proportion	*OMC*	*MDD*	*PL*	*LL*	*PI*	*CBR*	*UCS*
	(%)	(kg/cm³)	(%)	(%)	(%)	(%)	(kPa)
0TF + 0EF	25.70	1.43	42.71	78.71	36.00	2.85	36.50
0.25TF + 0.25EF	21.80	1.45	32.01	65.21	33.20	4.50	40.80
0.25TF + 0.50%EF	20.80	1.49	31.80	62.30	30.50	6.30	48.20
0.25TF + 0.75EF	19.90	1.55	30.08	60.28	30.20	8.10	52.30
0.25TF + 1.00 EF	19.80	1.60	30.10	60.00	29.90	9.60	60.60
0.5TF + 0.25EF	19.50	1.65	30.06	59.36	29.30	10.50	85.50
0.5TF + 0.50EF	19.40	1.68	29.25	57.55	28.30	10.90	180.20
0.5TF + 0.75EF	18.90	1.70	28.19	55.39	27.20	10.95	192.50
0.5TF + 1.00EF	18.40	1.74	27.47	53.87	26.40	11.60	210.50
0.75TF + 0.50 EF	17.60	1.77	27.13	52.63	25.50	12.10	220.60
0.75 TF + 0.75EF	17.10	1.79	27.05	51.95	24.90	12.60	242.80

CBR in laboratory can be time-consuming, and results may not always be accurate due to various influencing factors. Therefore, developing a linear regression model is crucial to address these challenges.

To resolve these issues, it is necessary to establish correlations between the *CBR* and factors such as *PI*, *OMC*, and *MDD*. These tests were conducted over a shorter period compared to the *CBR* test. (Taskiran, 2010; Bassey et al., 2017; Alam et al., 2020; Hassan et al., 2022)

3.4.1 Simple linear regression analysis model to predict *CBR*

To build the model, California Bearing Ratio as the dependent variable and *OMC*, *MDD*, and *PI* as independent variables were selected.

Table 5. Presentation of statistical output for *CBR* vs. *PI*.

Regression Statistics	
Multiple R	0.96
R Square	0.92
Adjusted R Square	0.91
Standard Error	0.96
Observations	11.00

3.4.1.1 Model Summary of CBR vs. PI

The statistical output for *CBR* vs. *PI* is presented in Table 5. The ANOVA output for *CBR* vs. *PI* is described in Table 6. The Coefficient of independent variable for *CBR* vs. *PI* is described in Table 7.

3.4.1.2 Model summary of CBR vs. OMC

The statistical output for *CBR* vs. *OMC* is described in Table 8. The ANOVA output for *CBR* vs. *OMC* is described in Table 9. The Coefficient of independent variable for *CBR* vs. *OMC* described in Table 10.

3.4.1.3 Model Summary of CBR vs. MDD

Statistical output for *CBR* vs. *MDD* is described in Table 11. The ANOVA output for *CBR* vs. *MDD* is described in Table 12. Coefficient of independent variable for *CBR* vs. *MDD* is described in Table 13.

Simple linear regression analysis was used to create a model describing the relationship between *CBR* and other properties of stabilized soil, such as, *PI*, *OMC*, and *MDD*. The resulting correlation values were 0.91, 0.86, and 0.93, respectively. These values are all close to one, indicating very good agreement and a strong positive linear relationship, meaning that one variable increases as the other does.

Table 6. Presentation of ANOVA output for *CBR* vs. *PI*.

ANOVA					
	df	*SS*	*MS*	*F*	Significance *F*
Regression	1.00	97.19	97.19	106.13	2.79E-06
Residual	9.00	8.24	0.92		
Total	10.00	105.43			

Table 7. Presentation of coefficient of independent variable for *CBR* vs. *PI*.

	Coefficients	Standard Error	*t* Stat	*P*-value	Lower 95%	Upper 95%
Intercept	36.52	2.68	13.64	2.57E-07	30.46	42.58
PI	-0.94	0.09	-10.30	2.79E-06	-1.15	-0.73

Table 8. Presentation of Statistical output for *CBR* vs. *OMC*.

Regression Statistics	
Multiple *R*	0.94
R Square	0.88
Adjusted *R* Square	0.88
Standard Error	1.19

Table 9. Presentation of ANOVA output for *CBR* vs. *OMC*.

ANOVA					
	df	*SS*	*MS*	*F*	Significance *F*
Regression	1.00	92.72	92.72	65.63	2.00E-05
Residual	9.00	12.72	1.412		
Total	10.00	105.43			

3.5 Prediction of *CBR* value from the index properties of treated soil by using multiple linear regression model

A multiple regression model was used to predict the *CBR* values based on several engineering properties of soil. The model was developed using *PI*, *OMC*, and *MDD* as variables, and a mathematical correlation was established to predict the *CBR* values (Equation 1).

$$CBR = -24.17 - 0.89\ OMC + 22.46\ MDD + 0.49\ PI \quad (1)$$

Intercept ($\beta_0 = -24.17$): The estimated *CBR* when *OMC*, *MDD*, and *PI* are all zero.
$\beta_1 = -0.89$: For every 1% increase in *OMC*, *CBR* decreases by 0.89 units, keeping *MDD* and *PI* constant.
$\beta_2 = 22.46$: For every 1-unit increase in *MDD*, *CBR* increases by 22.46 units, keeping *OMC* and *PI* constant.
$\beta_3 = 0.49$: For every 1-unit increase in *PI*, *CBR* increases by 0.49 units, keeping *OMC* and *MDD* constant. Experimental and Predicted *CBR* Value is described in Table 14 and Figure 9.

Table 10. Presentation of coefficient of independent variable for *CBR* vs. *OMC*.

	Coefficients	Standard Error	*t* Stat	*P*-value	Lower 95%	Upper 95%
Intercept	34.96	3.21	10.88	1.77E-06	27.70	42.23
OMC	-1.30	0.16	-8.10	2.00E-05	-1.66	-0.94

Table 11. Presentation of statistical output for *CBR* vs. *MDD*.

Regression Statistics	
Multiple *R*	0.97
R Square	0.94
Adjusted *R* Square	0.94
Standard Error	0.81
Observations	11

Table 12. Presentation of ANOVA output for *CBR* vs. *MDD*.

ANOVA					
	df	*SS*	*MS*	*F*	Significance *F*
Regression	1	99.55	99.55	152.17	6.09E-07
Residual	9	5.89	0.65		
Total	10	105.43			

Table 13. Presentation of coefficient of independent variable for *CBR* vs. *MDD*.

	Coefficients	Standard Error	*t* Stat	*P*-value	Lower 95%	Upper 95%
Intercept	-30.86	3.26	-9.50	5.47E-06	-38.21	-23.51
MDD	24.62	2.00	12.34	6.09E-07	20.11	29.14

Table 14. Experimental and predicted *CBR* Value.

Observation	Content of Stabilizer (%)	Predicted Value	Laboratory obtained Value	Residuals	% of Residual
1	0TF + 0EF	2.96	2.85	-0.11	4.55
2	0.25TF + 0.25EF	5.50	4.50	-1.00	13.64
3	0.25TF + 0.5%CA	5.95	6.30	0.35	22.73
4	0.25TF + 0.75EF	7.94	8.10	0.16	31.82
5	0.25TF + 1.0 EF	9.01	9.60	0.59	40.91
6	0.5TF + 0.25EF	10.10	10.50	0.40	50.00
7	0.5TF + 0.5EF	10.37	10.90	0.53	59.09
8	0.5TF + 0.75EF	10.72	10.95	0.23	68.18
9	0.5TF + 1EF	11.66	11.60	-0.06	77.27
10	0.75TF + 0.5 EF	12.60	12.10	-0.50	86.36
11	0.75 TF + 0.75EF	13.20	12.60	-0.60	95.45

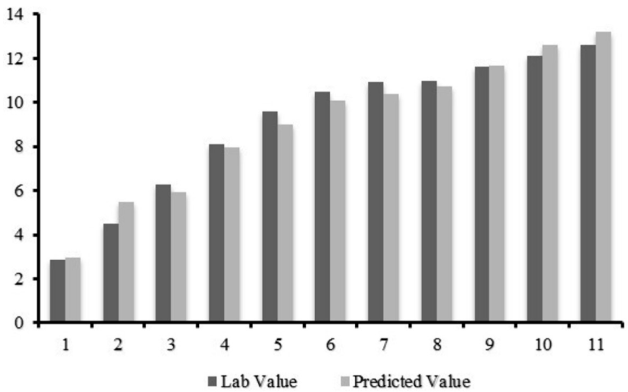

Figure 9. Predicted value vs. Laboratory value of *CBR*.

4. Conclusion

This research focuses on enhancing mechanical strength by utilizing two local natural fibers enset ventricosum fiber (kacha) and teff straw (chid). The selection of these fibers is guided by factors such as accessibility, tensile strength, agricultural productivity, and the abundance of by-products. The white color enset fiber has an average length of 2 meters, an average thickness of 0.02 mm, and a water absorbance of 50-60%. When the enset fiber is soaked for 24 hours, it exhibits a dry density of 690 kg/m^3 and demonstrates a strong tensile strength with a snap force of 15.4 N. In contrast, teff straw fiber becomes highly flexible when wet. It absorbs water at a rate of 40-50%, can break, when bent between 270 to 360 degrees, has an average length of 5 cm, an average thickness of 1 mm, and an average diameter of 0.3 mm. The addition of these fibers notably improved surcharge swell, *CBR*, *UCS*, and *MDD*. The research also determined that the optimum percentage of natural fibers to be added to the soil is approximately 0.75% enset ventricosum (kacha) and teff straw (chid) are used to improve the quality of expansive soil.

Furthermore, the study revealed that increasing the content of enset ventricosum fiber from 0.25% to 1% in the sub-grade soil resulted in an increase in *MDD*, *CBR*, and *UCS*, while decreasing the *OMC*. Additionally, the free swell percentage of fiber-conjugated soil decreased as the percentage of fiber increased. Statistical models were developed to predict the *CBR* value based on other index properties of the soil showing close agreement with experimental findings.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Tarun Kumar Lohani: conceptualization, data curation, visualization, supervision, writing – review & editing. Abrham Bassa Efamo: formal analysis, conceptualization, data curation, methodology, software, validation, writing – original draft.

Data availability

All data produced or examined in the course of the current study are included in this article.

Declaration of use of generative artificial intelligence

This work was prepared without the assistance of any generative artificial intelligence (GenAI) tools or services. All aspects of the manuscript were developed solely by the authors, who take full responsibility for the content of this publication.

List of symbols and abbreviations

vs.	versus
ANOVA	Analysis of Variance
AASHTO	American Association of State Highway and Transportation Officials
CBR	California Bearing Ratio
LL	Liquid Limit
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
PI	Plasticity Index
PL	Plastic Limit
UCS	Unconfined Compressive Strength
USCS	Unified Soil Classification System

References

Adem, H.H., & Vanapalli, S.K. (2015). Review of methods for predicting in situ volume change movement of expansive soil over time. *Journal of Rock Mechanics and Geotechnical Engineering*, 7(1), 73-78. https://doi.org/10.1016/j.jrmge.2014.11.002.

Afrin, H. (2017). A review on different types soil stabilization techniques. *International Journal of Transportation Engineering and Technology*, 3(2), 19-24. https://doi.org/10.11648/j.ijtet.20170302.12.

Alam, S.K., Mondal, A., & Shiuly, A. (2020). Prediction of CBR value of fine grained soils of bengal basin by genetic expression programming, artificial neural network and krigging method. *Journal of the Geological Society of India*, 95(2), 190-196. https://doi.org/10.1007/s12594-020-1409-0.

Ali, M. (2011). Coconut fibre: a versatile material and its applications in engineering. *Journal of Civil Engineering* *and Construction Technology*, 2(9), 189-197. Retrieved in June 17, 2025, from http://www.academicjournals.org/jcect

Al-Kalili, A., Ali, A.S., & Al-Taie, A.J. (2022). A review on expansive soils stabilized with different pozzolanic materials. *Journal of Engineering*, 28(1), 1-18. https://doi.org/10.31026/j.eng.2022.01.01.

Anagnostopoulos, C.A., Tzetzis, D., & Berketis, K. (2013). Shear strength behaviour of polypropylene fibre reinforced cohesive soils. *Geomechanics and Geoengineering*, 9(3), 241-251. https://doi.org/10.1080/17486025.2013.804213.

Ashour, T., Wieland, H., Georg, H., Bockisch, F.J., & Wu, W. (2010). The influence of natural reinforcement fibres on insulation values of earth plaster for straw bale buildings. *Materials & Design*, 31(10), 4676-4685. https://doi.org/10.1016/j.matdes.2010.05.026.

Bassey, O.B., Attah, I.C., Ambrose, E.E., & Etim, R.K. (2017). Correlation between CBR values and index properties of soils: a case study of Ibiono, Oron and Onna in Akwa Ibom State. *Resources and Environment*, 7(2), 94-102.

Bekkouche, S.R., Benzerara, M., Zada, U., Muhammad, G., & Ali, Z. (2022). Use of eco-friendly materials in the stabilization of expansive soils. *Buildings*, 12(10), 1770. https://doi.org/10.3390/buildings12101770.

Birmeta, G., Nybom, H., & Bekele, E. (2004). Distinction between wild and cultivated enset (Ensete ventricosum) gene pools in Ethiopia using RAPD markers. *Hereditas*, 140(2), 139-148. https://doi.org/10.1111/j.1601-5223.2004.01792.x.

Cao, Z., Ma, Q., & Wang, H. (2019). Effect of Basalt fiber addition on static-dynamic mechanical behaviors and microstructure of stabilized soil compositing cement and fly ash. *Advances in Civil Engineering*, 2019(1), 8214534. https://doi.org/10.1155/2019/8214534.

Chala, G., Quezon, E.T., Mekonnen, E., & Ararsa, W. (2020). Effects on modified properties of expansive clay soil using waste hollow concrete block (HCB) and cement plaster waste materials for subgrade construction. *International Journal of Research–Granthaalayah*, 8(3), 342-347. https://doi.org/10.29121/granthaalayah.v8.i3.2020.168.

Chauhan, M.S., Mittal, S., & Mohanty, B. (2008). Performance evaluation of silty sand subgrade reinforced with fly ash and fibre. *Geotextiles and Geomembranes*, 26(5), 429-435. https://doi.org/10.1016/j.geotexmem.2008.02.001.

Correia, A.A.S., Venda Oliveira, P.J., & Custódio, D.G. (2015). Effect of polypropylene fibres on the compressive and tensile strength of a soft soil, artificially stabilised with binders. *Geotextiles and Geomembranes*, 43(2), 97-106. https://doi.org/10.1016/j.geotexmem.2014.11.008.

Dang, L.C., Fatahi, B., & Khabbaz, H. (2016). Behaviour of expansive soils stabilized with hydrated lime and bagasse Fibres. *Procedia Engineering*, 143, 658-665. https://doi.org/10.1016/j.proeng.2016.06.093.

Dessalegn, E. (2019). Effect of traditional fermentation time on total phenolic content and in vitro antioxidant activity of kocho: ethiopian fermented food from enset (Ensete ventricosum welw. Chessman). *Food Science and Quality Management*, https://doi.org/10.7176/FSQM/91-05.

Esayas, E., Agon, E.C., & Assefa, S. (2018). Development of wall construction material stabilized with Enset vegetable fibers for rural housing units. *American Journal of Civil Engineering and Architecture*, 6(2), 54-62. https://doi.org/10.12691/ajcea-6-2-2.

Feleke, N., & Tekalign, W. (2022). The neglected traditional Enset (Ensete ventricosum) crop landraces for the sustainable livelihood of the local people in Southern Ethiopia. *International Journal of Food Sciences*, 2022(1), 6026763. https://doi.org/10.1155/2022/6026763.

Firoozi, A.A., Guney Olgun, C., Firoozi, A.A., & Baghini, M.S. (2017). Fundamentals of soil stabilization. *International Journal of Geo-engineering*, 8(1), 1-16. https://doi.org/10.1186/s40703-017-0064-9.

Ghavami, K., Toledo Filho, R.D., & Barbosa, N.P. (1999). Behaviour of composite soil reinforced with natural fibres. *Cement and Concrete Composites*, 21(1), 39-48. https://doi.org/10.1016/S0958-9465(98)00033-X.

Hassan, J., Alshameri, B., & Iqbal, F. (2022). Prediction of California Bearing Ratio (CBR) using index soil properties and compaction parameters of low plastic fine-grained soil. *Transportation Infrastructure Geotechnology*, 9(6), 764-776. https://doi.org/10.1007/s40515-021-00197-0.

Hejazi, S.M., Sheikhzadeh, M., Abtahi, S.M., & Zadhoush, A. (2012). A simple review of soil reinforcement by using natural and synthetic fibers. *Construction & Building Materials*, 30, 100-116. https://doi.org/10.1016/j.conbuildmat.2011.11.045.

Hossain, M.A., Hossain, M.S., & Hasan, M.K. (2015). Application of jute fiber for the improvement of subgrade characteristics. *American Journal of Civil Engineering*, 3(2), 26. https://doi.org/10.11648/j.ajce.20150302.11.

Khan, S.Z., Rehman, Z., Khan, A.H., Qamar, S., & Haider, F. (2021). Effect of polypropylene fibers and cement on the strength improvement of subgrade lying on expansive soil. *Civil Engineering*, 46(1), 343-352. https://doi.org/10.1007/s40996-021-00790-w.

Kunyanga, C.N., Imungi, J.K., Okoth, M.W., Biesalski, H.K., & Vadivel, V. (2012). Total phenolic content, antioxidant and antidiabetic properties of methanolic extract of raw and traditionally processed Kenyan indigenous food ingredients. *Lebensmittel-Wissenschaft + Technologie*, 45(2), 269-276. https://doi.org/10.1016/j.lwt.2011.08.006.

Mahedi, M., Cetin, B., & White, D.J. (2020). Cement, lime, and fly ashes in stabilizing expansive soils: performance evaluation and comparison. *Journal of Materials in Civil Engineering*, 32(7), 04020177. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003260.

Maniyazawal, F.W. (2020). Replacing cinder gravel as alternative base course material. *American Journal of Construction and Building Materials*, 4(1), 14-21. https://doi.org/10.11648/j.ajcbm.20200401.13.

Nwachukwu, N., & Eburukevwe, O. (2013). Assessment of environmental hazards: linking borrow pits, gully erosion, and road failure. *Journal of Civil Engineering*, 4(6), 199-210.

Prabakar, J., & Sridhar, R.S. (2002). Effect of random inclusion of sisal fibre on strength behaviour of soil.

Construction & Building Materials, 16(2), 123-131. https://doi.org/10.1016/S0950-0618(02)00008-9.

Taskiran, T. (2010). Prediction of California bearing ratio (CBR) of fine grained soils by AI methods. *Advances in Engineering Software*, 41(6), 886-892. https://doi.org/10.1016/j.advengsoft.2010.01.003.

Torgal, F.P., & Jalali, S. (2011). Natural fiber reinforced concrete. In R. Fangueiro (Ed.), *Fibrous and composite materials for civil engineering applications* (pp. 154-167). Woodhead Publishing. https://doi.org/10.1533/9780857095583.2.154.

Wang, J.-S., Wu, G., Zhao, Z.-M., Li, L., Lian, Q., & He, L. (2020). Experimental study on factors influencing the expansive properties of disturbed swelling rock. *Soil Mechanics and Foundation Engineering*, 57(1), 84-91. https://doi.org/10.1007/s11204-020-09641-8.