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Optimization of physical and strength performance of cellulose-based fiber additives stabilized expansive soil

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ABSTRACT

Expansive soils are known as geotechnically problematic soils and represent a significant challenge for both civil engineering and geotechnical applications. The primary issue with expansive soils is their susceptibility to moisture-induced volume changes, resulting in both shrinkage and swelling behaviors. This study presents a comprehensive investigation into optimizing the physical and strength properties of expansive soil through the use of cellulose-based fiber additives, namely bamboo fiber (BF), rice husk fiber (RHF), and wheat straw fiber (WSF). Various fiber dosages (5 %, 10 %, and 15 %) and sizes (75 μm, 150 μm, and 300 μm) were employed in combinations to identify the optimal conditions and analyze the soil-fiber reinforcement mechanisms. The experimental design was leveraged by the Taguchi method to optimize conditions, focusing on key response factors such as the Atterberg limit test (PI, LL), free swell ratio (FSR), linear shrinkage (LS), and unconfined compressive strength (UCS) and statistical analysis for results were validated by Analysis of Variance (ANOVA). Additionally, cellulose content and water absorption capacity were assessed to confirm the suitability of cellulose-based fibers as soil stabilizers. Hence, the results demonstrate a substantial enhancement in both the physical and mechanical properties of the stabilized soil with the incorporation of cellulose-based fiber additives. Specifically, the Plastic Index (PI) improved by 85 % when using RHF fibers at a dosage and size of 15 % and 300 μm, respectively. The Free Swell Ratio (FSR) witnessed improvement with WSF fibers at a dosage of 15 % and a size of 150 μm. Linear shrinkage exhibited remarkable improvement, exceeding 95 %, with a combination of 15 % and 75 μm fibers. Furthermore, the Unconfined Compressive Strength (UCS) values were improved by more than 100 % when using 15 % BF fibers with a size of 300 μm. Therefore, the findings of the study highlight that cellulose-based additives as highly effective and sustainable alternatives for soil stabilization, surpassing the engineering performance of traditional soil stabilizers

1. Introduction

Expansive soils are recognized as geotechnically challenging soils. They present a major problem in the fields of civil engineering and geotechnical applications. The main problem revolves around moisture variations that result in volumetric changes associated with the phenomena of contraction and expansion. Several attempts have been undertaken by researchers and geotechnical engineers

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to solve the problems associated with expansive soils. Some of them are expansive soil stabilization with natural fibers extracted from agricultural waste products. Recently, due to their versatile applicability and manufacturability, cellulose-based fibers have attracted the attention of various researchers and geotechnical engineers [1–4]. Cellulose-based fibers are mainly byproducts of plants, trees, and vegetation. These fibers are the most widely and abundantly available type of natural fiber on earth [5,6]. Compared to synthetic fibers and traditional soil stabilizers, cellulose-based fibers offer several advantages for geotechnical usage, including reinforcement capabilities, erosion control, soil improvement, sustainability, and cost-effectiveness [4,5,7]. Expansive soils stabilized with cellulose-based fibers have shown significant improvements. These include reduced shrinkage and swelling, increased physical and mechanical strength, reduced settlement, and increased structural stability [7–9].

The most common cellulosic fibers used to stabilize soil are coir, straw, wood fiber, hemp, sisal, bagasse, and jute fibers. In addition to soil stabilization, these fibers can be used in medicine, electronics, food, textiles, and many other applications [10–13]. On the other hand, agricultural waste contributes to a large part of the global accumulation of waste and causes a serious problem for the environment and ecosystems. In several countries, mountains of different types of agricultural waste are produced every year. This poses a problem for the environment if not properly managed [14–16]. In several previous studies, researchers have used agricultural waste in the form of ash for soil stabilization with the aim of inducing the pozzolanic reaction and agglomeration in the soil particles. However, the efficiency of using agricultural waste in the form of ash depends on the type of soil to which it is added. For instance, the amount of ash produced by combustion might not be sufficient and it requires considerable energy to produce [17,18].

In this study, the cellulose-based fibers used for soil stabilization are derived from natural sources such as agricultural waste products that could possibly offer sustainable and environmentally friendly alternatives. Several attempts have been made by researchers to use agricultural waste products for the benefit of soil reinforcing and strengthening, absorbing excess water, thermal resistance, and improving soil engineering properties, sustainability, durability, and cost-effectiveness [14,19–21]. According to Hongzhou et al. [12], the use of cellulose-based fibers could regulate moisture migration and create a more stable and resistant soil matrix. The fiber content and size of the cellulose materials could be adjustable, and thus, they are suitable for a variety of soil-reinforcement methods [9,22,23].

This study, therefore, delved into an exploration of different combinations of cellulose fiber content and size, seeking to identify the most favorable conditions concerning key response factors, including the Atterberg limits, free swell ratio (FSR), linear shrinkage (LS), and unconfined compressive strength (UCS). The primary aim of this research was to assess enhancements in strength parameters, specifically UCS values, along with other geotechnical properties like Plastic Index (PI), Free Swell Ratio (FSR), and Linear Shrinkage (LS) using bamboo fiber, rice husk fiber, and wheat straw fiber dosages and sizes combinations. Additionally, the study evaluated how cellulose-based fibers impact stabilized soils under optimal conditions determined through the Taguchi method. In doing so, it aimed to promote the adoption of natural and sustainable fiber materials derived from waste products as an eco-friendly alternative to traditional soil stabilizers such as cement and lime.

2. Experimental design

This section discusses the details of the experimental designs of the study. The materials used in this study such as expansive black cotton soil and cellulose-based additives extracted from the agricultural waste will be discussed in subsection (i) and the experimental procedures will be discussed in subsection (ii).

2.1. Materials

A) Pseudo-expansive black cotton soil (BCS)

Expansive black cotton soil is a largely plastic clay soil that is prone to excessive swelling, threatening the stability of built structures [9]. It is often characterized as a geotechnically problematic soil due to the presence of highly swelling clay minerals, i.e., montmorillonite, kaolinite, illite, and quartz [24,36]. The expansive black cotton soil doesn't exist in Japan with similar characteristics of expansive soil found in other regions. However, this study made an attempt to replicate the pseudo-expansive soil from the combination of clay soils that have similar characteristics to the original soil. Therefore, the clay soils were collected from commercial sources in Japan and composed of Kunigel V1, Kasaoka, and Tochi clay soils. Similar experiences were seen with the fabric/manufacture of soil to study the mechanical and physical properties of clay soils [24,25]. The quantities of each soil incorporated into the mixture were determined through a combination of prior expertise, analysis of clay content, soil texture, and examination of experimental results, particularly the liquid limit, free swelling ratio, and mineralogy data as preliminary investigation, as illustrated in Table 1. In addition, the basic geotechnical characteristics of the replicated and original expansive soil are described in Table 2.

Cellulose-based fibers can be used in a variety of applications as an environmentally friendly and sustainable material. In this study,

Table 1
Estimated clay soil proportions for replicated pseudo-expansive soil.

S. No.	Clay soil name	Estimated proportion, %	Replicated soil name
1	KunigelV1	21.8	Pseudo-expansive soil - PES
2	Kasaoka clay	39.1	
3	Tochi clay	39.1	

cellulose-based fibers from different agricultural waste materials were evaluated for their applicability and suitability aspects. The fiber size, content, water-absorbing capacity, and strength of the fibers are the key factors when selecting cellulosic fibers as potential soil stabilizers [4,26,27]. In addition, these materials help to improve the strength and stability of the soil by creating a reinforcing matrix that helps to hold the soil particles together, thus improving the bearing capacity and durability of the soil [28–30]. The fiber preparation process of the fiber materials is shown in Fig. 1. The cellulose-based materials collected from agricultural waste sources must be crushed into smaller sizes of fibers and then separated by size using a sieve shaker.

2.2. Experimental procedures

The experimental procedures for cellulose-based fiber stabilized soils typically involve extensive laboratory testing to evaluate the effects of fiber inclusion on the mechanical and physical properties of the stabilized soil. It is also essential to understand the mechanism of fiber inclusion, which improves the geotechnical properties of the stabilized soil. In addition, the effect of cellulose fiber on the stabilized soil should be analyzed by the Taguchi method and supported by ANOVA statistical analysis.

The fibers physically interlock with the soil particles, forming a network of reinforcement. According to a study by Hejazi et al. [31], the fibers prevent excessive soil particle movement by bridging the gaps between particles when the soil is stressed. This also prevents localized shear failure by distributing the load more evenly throughout the soil matrix [12,32]. The fibers create frictional forces that resist soil movement, effectively increasing the overall shear strength of the reinforced soil [23,33,34]. The mechanical characteristics of stabilized soil with fibers exhibit higher UCS values. The expansive soil reinforced with fiber shows 55–68 % time higher strength than unreinforced soil [35,36]. The fibers could also act as bridges to reduce the cracking and increase the soil strength.

A) Taguchi method

In this study, the experimental procedure was based on the Taguchi method of Design Level 9 (L9) Design of Experimental approach [37–39]. This method was used to optimize the conditions and to identify the most significant factor that affects the results of the process (outcome) [37,40,41]. The Taguchi method is used in soil stabilization to systematically optimize and improve the performance of soil stabilizers, such as cellulose-based fibers. This method helps identify the best combination of factors, such as fiber dosage and size, by conducting controlled experiments to improve key soil properties, such as strength and compaction, while minimizing the number of tests required, and reducing the optimization time and effort [42–44]. In the conventional way of conducting an experiment with various variables and factors, it is difficult to reach an acceptable result. The results might be biased and scientifically less proven. Hence, due to this reason, we employed the Taguchi Orthogonal Array (OA) technique in conjunction with Minitab software to design our experiment efficiently. Orthogonal arrays enable the execution of a minimal number of experiments while providing comprehensive information about all factors affecting performance parameters [37,38]. To meet this requirement, we utilized three response factors with three corresponding design levels (L9–33) to create the most effective experimental design matrix for our research. Additionally, we applied the Analysis of Variance (ANOVA) technique as a statistical tool to assess data significance and variable contributions within the testing conditions.

This approach allowed us to identify and optimize the most promising cellulose-based fiber materials for soil stabilization. Careful consideration was given to the design of response variables and their coefficients to ensure that our experiments were likely to yield the desired outcomes [38,41]. By optimizing all test runs within the experiment, better insights can be gained into the influence of each factor on performance results [45–47]. Tables 3 and 4 present the design matrix and experimental design code, respectively. To ensure result quality and repeatability, the test runs were performed three times independently for each response factor. In total, 27 experiments were conducted under the designed experimental conditions. Ultimately, we utilized the S/N (signal-to-noise) ratio provided by the Taguchi method to determine the optimal cellulose-based fiber additive, considering various response factor parameters described in Tables 3 and 4 respectively.

Atterberg limit test: The Atterberg limit test is a standard method in soil science and geotechnics for determining the plasticity index of soils. Atterberg limits are well known for soil classification and prediction of soil behavior under moisture variations. The method has been in use for many years as a reliable engineering method for evaluating the consistency of the soil index characteristics for the design and construction of civil infrastructures [48]. The test determines three different soil limits: liquid limit, plastic limit, and shrinkage limit. The standard ASTM D4318 test method was used to determine these liquid, plastic, and shrinkage limits. The liquid limit is defined as the minimum moisture content at which a soil flows when a very small shear force is applied. It is primarily used by civil and geotechnical engineers as a physical characteristic of soils. The plastic limit is the water content of the soil at the boundary between the plastic and semisolid states. It expresses the difference between the liquid values and the plastic limit values. This test

Table 2
Geotechnical characteristics of pseudo-expansive soil and expansive black cotton soil.

Sample No.	Soil name	LL, %	PL, %	PI, %	FSR, %	OMC, %	MDD, %	CBR, %	UCS, kPa	P, %
1	PSE	103.4	25.7	77.7	1.5	29	1.38	–	105.7	25
2	ES	106.4	42.2	64.6	1.98	30	1.40	1.1	84.8	–

PES: pseudo-expansive soil, ES: expansive soil, LL: liquid limit; PL: plastic limit; PI: plastic index; FSR: free swell ratio; OMC: optimum moisture content; MDD: maximum dry density: CBR: California bearing ratio; UCS: unconfined compressive strength, P: porosity

B) Cellulose-based fiber materials

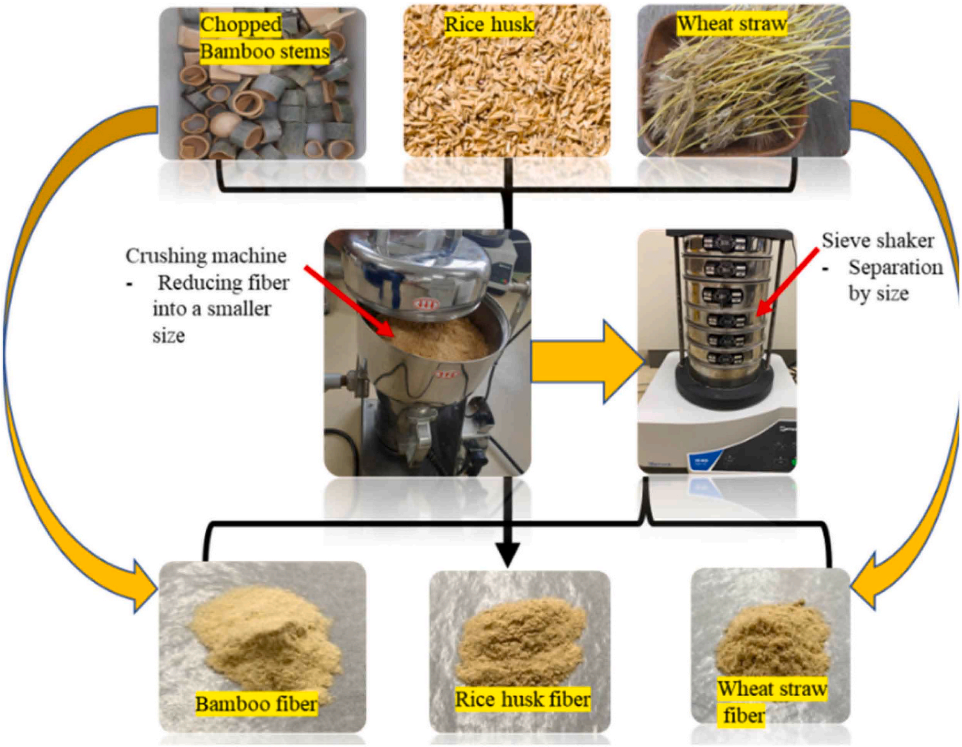


Fig. 1. Fiber Production process of cellulosic fibers from agricultural waste.

Table 3
L9 OA test run conditions for respective response factors.

Factor	Parameter factor	Unit	Level 1	Level 2	Level 3
A	Cellulose-based fiber	–	BF	RHF	WSF
B	Cellulose fiber content	%	5	10	15
C	Fiber size	μm	75	150	300

BF: BF: bamboo fiber, RHF: rice husk fiber, WSF: wheat straw fibers

Table 4
Response factors and parameters along with corresponding levels.

Trial No.	Cellulose-based fiber	Cellulose content, %	Fiber size, μm	Coded test design		
PES	–	–	–	0	0	0
1	BF	5	75	1	1	1
2	BF	10	150	1	2	2
3	BF	15	300	1	3	3
4	RHF	5	150	2	1	2
5	RHF	10	300	2	2	3
6	RHF	15	75	2	3	1
7	WSF	5	300	3	1	3
8	WSF	10	75	3	2	1
9	WSF	15	150	3	3	2

PES: pseudo-expansive soil, BF: bamboo fiber, RHF: rice husk fiber, WSF: wheat straw fiber

B) Geo-mechanical characteristics

should be carried out for soil samples stabilized with cellulose-based fibers and without additives [48,49].

Particle size distribution: A particle size distribution test is conducted to determine the soil classification and to evaluate the soil characteristics in terms of the clay, silt, and sand fractions. The mechanism of the particle size distribution of clay minerals can be used to understand the swelling and shrinking potential of expansive soils [50,51]. The ability of soils to swell and shrink greatly depends on the presence of fine particles, especially clay-sized particles. The Mastersizer 3000 particle size analyzer was used to analyze the pseudo-expansive soil particle size distribution. The instrument is assisted by software and simultaneously evaluates the data obtained from the test. Fig. 2 depicts the particle size analysis of the pseudo-expansive soil, using the Masterzizer 3000 analyzer, and the hydrometer analysis. As shown in the figure, the D10, D50, and D90 values are important indicators of the particle size distribution curve. Thus, a sample can be represented as very fine-grained clay, with more than 90 % of the particles in the sample being smaller in size [52,53].

A particle size distribution analysis of fine-grained soils, using a hydrometer analysis, is important because it provides valuable information on the fraction of different particle sizes present in a soil sample, which is critical to understanding its engineering and geotechnical properties. This test is designed to accurately measure the amounts of clay and silt, and the clay content. To conduct the experiment, finely ground soil is prepared and blended with distilled water using sodium hexametaphosphate as a dispersing agent. The prepared samples are mixed with a high-speed blender and poured into a 1000-ml graduated cylinder. A meniscus apparatus is set up to record the suspension and settling of the soil particles at specified time intervals [50,52,54].

Free swell ratio test: This is a simple test to determine the potential swelling behavior of soils. The test procedure is as follows: 2 g of the oven-dried soil sample is passed through a 425-μm sieve for each of two 100-ml graduated cylinders. Distilled water (Vd) is added to one cylinder and kerosene (Vk) is added to the other. The prepared samples are to be added very slowly, about 0.2 g at a time, and sufficient time must be allowed to elapse so that the soil settles completely, as shown in Fig. 3. A simple calculation technique for free swell ratio (FSR= Vd/Vk) was used to evaluate the changes in the soil.

Linear shrinkage test: The linear shrinkage test is used to determine the amount of shrinkage that occurs in a soil sample as it loses moisture. This test is particularly important to understand the behavior of soil when it undergoes changes in moisture content. Linear shrinkage is a measure of the decrease in dimensions of a soil sample as it dries out. The methods used to conduct the test are described in several international standards such as ASTM D423–1966, AASHTO T 238 IS2720, AS1289, and JGS 0145. However, in this test, AS1289 is used as a reference to conduct the linear shrinkage test. The material used for the liquid limit can be used by adding a sufficient amount of water to bring it to a consistency equal to or slightly wetter than the liquid limit. After placing the specimen on the shrinkage mold, dry the specimen for 24 h until changes in color are observed, and then transfer to oven at between 105 °C–110 °C. Measure the longitudinal shrinkage Ls to the nearest mm after the oven dry and if there is a crack firmly hold and measure the length. Hence, the Linear Shrinkage, (LS) of the specimen is,

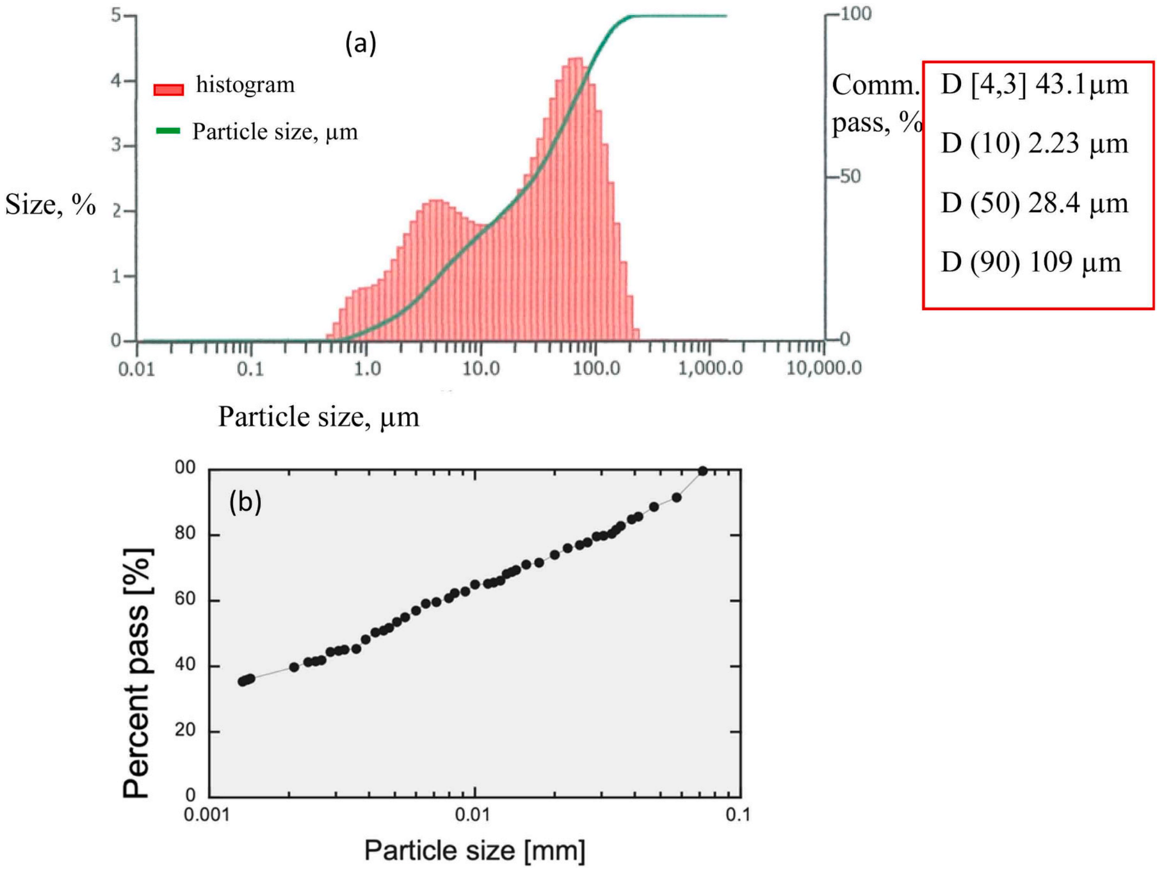


Fig. 2. Particle size analysis for pseudo-expansive soil: a) master-sizer 3000 and b) hydrometer analysis.

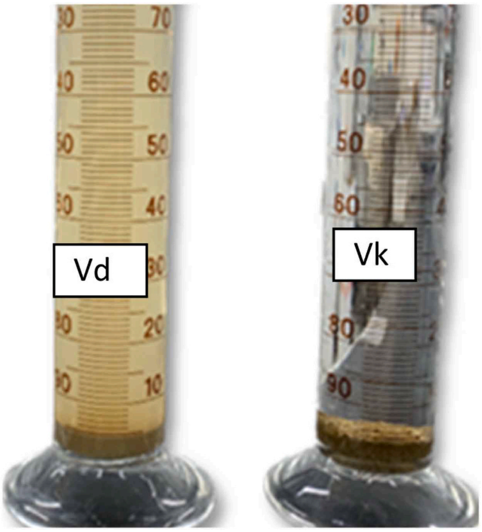


Fig. 3. Procedure for evaluation of free swell ratio (left: distilled water-Vd, right: kerosene-Vk).

$$LS\% = \frac{Ls}{L} * 100 \tag{1}$$

L= internal length of the mold, Ls= longitudinal shrinkage of the specimen.

Unconfined compressive strength test: This test is performed by applying a vertical compressive force to a free-standing specimen without lateral restraint. The unconfined compressive strength (UCS), which is the maximum compressive stress, is determined from this test. In this study, it was necessary to investigate the compaction density and moisture relationship between the non-stabilized expansive soil and the cellulose-based fiber-stabilized soil. The results of OMC from the compaction test were used to prepare the UCS test specimens with cellulose-based fiber additives.

The UCS test was employed to assess the stress-strain relationship and maximum stress of cellulose-based fiber-stabilized soil. Smaller split standard compaction molds were utilized, resulting in reduced compaction energy and fewer blows per layer. Specifically, the energy input was decreased to 12 blows per layer, the mold dimensions were reduced to a diameter of 50 mm and a height of 100 mm, and the rammer's drop height was lowered to 20 cm. The specimens were carefully positioned at the center of the lower compression plate, and loading was executed with precise displacement control at a loading speed of 1.0 mm/min.

In addition, a smaller amount of soil sample is required in the case of lower compaction energy. Based on this assumption, two important parameters were considered. The first one is (eC), compaction energy and the second one is (nB), the number of blows for each layer of the sample. Table 5 clearly shows that it is possible to obtain the same degree of compaction using split mold compaction with reduced energy. Similar conditions have been studied by other researchers in terms of a reduction in compacting energy [14,24,64]. A comparison between standard compaction and split mold compaction (with reduced energy) is shown Table 5.

The comparison of energy effort given in Table 4.5 was obtained from a formula designed to determine the reduced compaction energy effort (eC), as follows:

The compaction effort (eC) applied to the soil/unit volume is

$$eC = \frac{wR * hD * nL * nB}{sV} \tag{2}$$

To reduce the compaction effort at a dry density of 95 % of standard compaction, it is essential to determine the number of blows per layer in the split mold; hence, nB.

$$nB = \frac{eC * sV}{wR * hD * nL} \tag{3}$$

Table 5
Comparison of compaction energy effort.

S. No.	Compaction type	D, mm	H, mm	V, cm^3	Mms, g	Mm, g	Bd, g/cm^3	Dd, g/g	B/L	DC, % @ 95%MDD
1	Standard compaction	100	125.4	1000	6130	4532	1.61	1.15	25/3	98.02
2	Split mold compaction	50	100	196.4	2340	1962	1.58	1.12	12/3	

D: mold diameter, H: mold height, V: volume, Mms: mass of mold+soil, Mm: mass of mold, Bd: bulk density, Dd: dry density, B/L: number of blows/layers, DC: degree of compaction

Where, eC: compaction effort; w*R*: rammer weight; hD: rammer drop height; nL: number of layers; nB: number of blows; sV: volume of specimen.

C) Characteristics of cellulose-based fibers

It is essential to characterize the suitability of cellulose-based fibers before using them as potential soil stabilizers. The physical, mechanical, and chemical properties of these materials need to be evaluated in terms of strength, water absorption, thermal resistance, and reinforcement properties. Hence, this study focused on the quantification of the cellulose content, water-absorbing capacity, particle size analysis, and Fourier Transform Infrared Spectroscopy (FTIS) analysis of cellulose-based fiber materials. All the tests were carried out without any prior fiber treatment or moisture intervention in an oven.

Evaluation of cellulose: In terms of the soil stabilization process, this property is one of the most important characteristics of cellulose-based fibers. Cellulose is a complex carbohydrate that is the primary structural component of cell walls in crops, which includes cellulosic fibers like bamboo, wheat straw, and rice husk [3,11]. The mechanism of evaluating cellulose from cellulose-based fibers involves several steps, starting from determining the fiber properties, cellulose, hemicellulose, holocellulose, and lignin contents [55,56]. This evaluation helps in the identification of different materials with higher cellulose contents and better fiber properties.

There are several processes that can be used to extract cellulose from natural fiber materials. They include chemical and mechanical pulping, enzymatic hydrolysis, acid hydrolysis, ionic liquid dissolution, and alkaline extraction [26,56,57]. Some researchers may use a combination of techniques to achieve the desired results. However, the choice depends on the specific application and intended use of the natural fiber materials [5,58]. In this research, acid hydrolysis and alkaline extraction processes were used together with mechanical pulping to extract the cellulose from the natural cellulose fiber materials. The detailed process for evaluating and extracting the cellulose content has been well documented in several studies [5,55,56,59]. The physical properties of the cellulose-based fiber materials used for stabilized expansive soil are presented in Table 6.

Evaluation of water-absorbing capacity: The water-absorbing capacity of cellulose-based fibers is one of the important features for describing the quality of materials with respect to performance and strength [60,61]. Some cellulose-based fibers are hydrophilic, having a high water-absorbing capacity, while others are hydrophobic, repelling water and having a low water-absorbing capacity [62]. This research considered cellulose-based fibers with a high water-absorbing capacity, mainly focusing on stabilized soil with water retention ability, which can improve soil stability and strength [27,63,64]. Moreover, Cellulose fibers are hydrophilic, which means they have a natural affinity for water molecules. This hydrophilic property results from the presence of numerous hydroxyl (-OH) groups along the cellulose polymer chains[11,23]. Melkamu et al.[60] investigated that when cellulose fibers come into contact with water, these hydroxyl groups attract and interact with water molecules through hydrogen bonding. As cellulose fibers swell, they increase in volume and length[60,65]. As the fibers expand, they create interlocking points with adjacent soil particles. This interlocking effect increases the cohesion between soil particles, effectively binding them together[27,31,66]. The fiber-soil matrix becomes more resistant to particle movement and deformation, contributing to improved stability[27,67].

Therefore, the mechanism of water absorption of cellulose fibers in soil stabilization involves the interaction between cellulose's hydrophilic properties, capillary action, hydrogen bonding, and the resulting swelling[60,68,69]. The swelling process increases the flexibility and pliability of the fibers, allowing them to adapt to the soil particles in the surrounding area[27]. Hence, cellulose-based fibers, such as bamboo, rice husk, and wheat straw fibers, are crushed with a high-speed mill and dried at room temperature. The maximum time for the water absorption of each material must be analyzed, and the capacity for absorbing water should be evaluated in the end. This will help in the understanding of the state of the peak of the water absorption and the steady absorption over a continuous period of time.

Several researchers have reported that the water-absorbing capacity may be affected by many factors, including surface roughness/smoothness, treatment agent, crystallinity, cellulose content, and fiber aspect ratio [70,71]. Fig. 4 presents the procedure for the water absorption test for cellulose-based fibers.

Particle size distribution: The particle size distribution is a key measure for understanding the fiber's physical properties and performance. It includes size uniformity, fiber distribution, stability, and performance when used for specific applications [11,13]. In this research, after crushing the cellulose-based fibers into fine particles, a mechanical sieve shaker was used to identify the various particle sizes passing through each sieve, starting from 1.18 mm, into the pan.

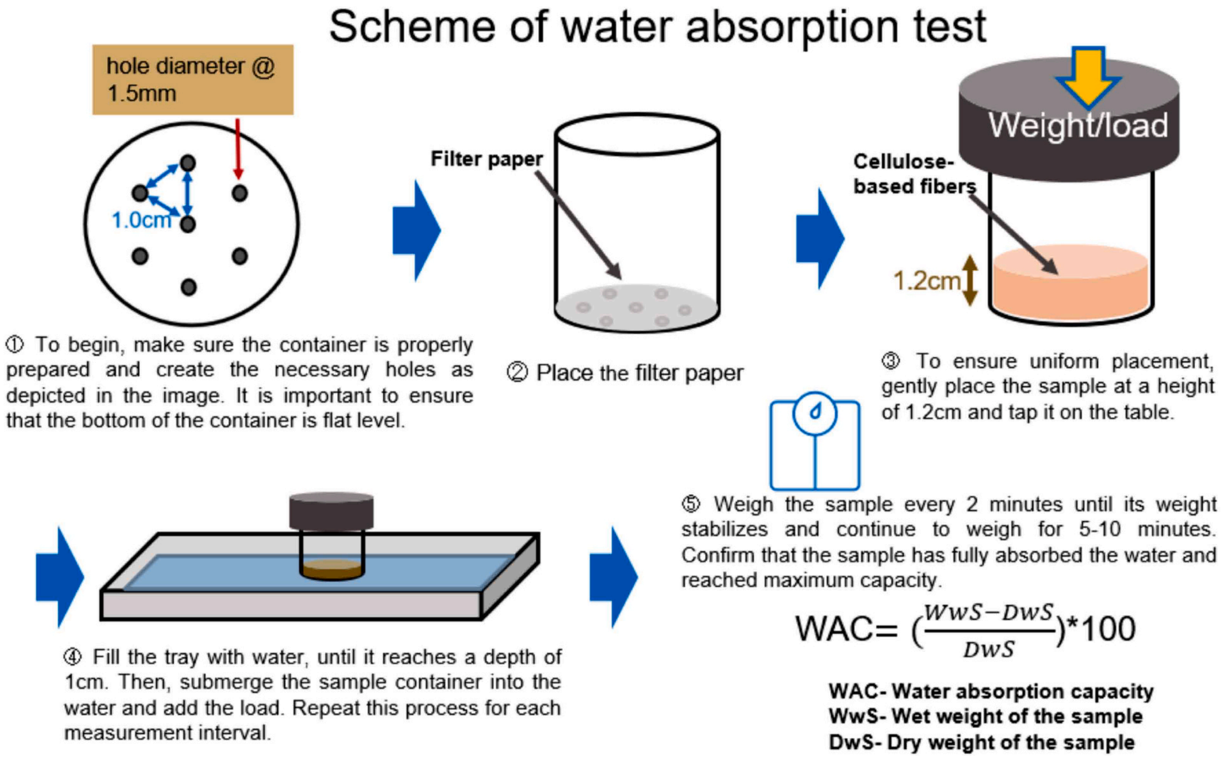
Then, the weight of the retained samples in each sieve was measured, and the cumulative percentage passing was calculated. The particle size distribution curve for the cellulose-based fibers is shown in Fig. 5.

FTIR analysis: FTIR (Fourier Transform Infrared Spectroscopy) analysis is used to identify and quantify various chemical components in cellulose-based fibers. It is a widely used technique to ensure the qualitative measurement process and to analyze the wide range in compounds in the fibers, polymers, minerals, and organic and inorganic materials [2]. FTIR also provides valuable

Table 6
Physical properties of cellulose-based fiber additives.

S. No.	Cellulose-based fiber	Source	L, mm	D, μm	Mc, %	C, %	Hc, %	WAC, g/g
1	Bamboo fiber	Stem	<1.5	300	7.05	49.5	29.8	5.2
2	Rice husk fiber	Stalk	<1	300	8.2	42.5	43.0	2
3	Wheat straw fiber	Stalk	<1.5	300	6.9	43	30.5	5.5

L: length, D: diameter, Mc: moisture content, C: cellulose content, Hc: hemicellulose, WAC: water absorption capacity



① To begin, make sure the container is properly prepared and create the necessary holes as depicted in the image. It is important to ensure that the bottom of the container is flat level.

② Place the filter paper

③ To ensure uniform placement, gently place the sample at a height of 1.2cm and tap it on the table.

④ Fill the tray with water, until it reaches a depth of 1cm. Then, submerge the sample container into the water and add the load. Repeat this process for each measurement interval.

⑤ Weigh the sample every 2 minutes until its weight stabilizes and continue to weigh for 5-10 minutes. Confirm that the sample has fully absorbed the water and reached maximum capacity.

$$WAC = \left(\frac{WwS - DwS}{DwS}\right)*100$$

WAC- Water absorption capacity
WwS- Wet weight of the sample
DwS- Dry weight of the sample

Fig. 4. Scheme of water absorption evaluation process.

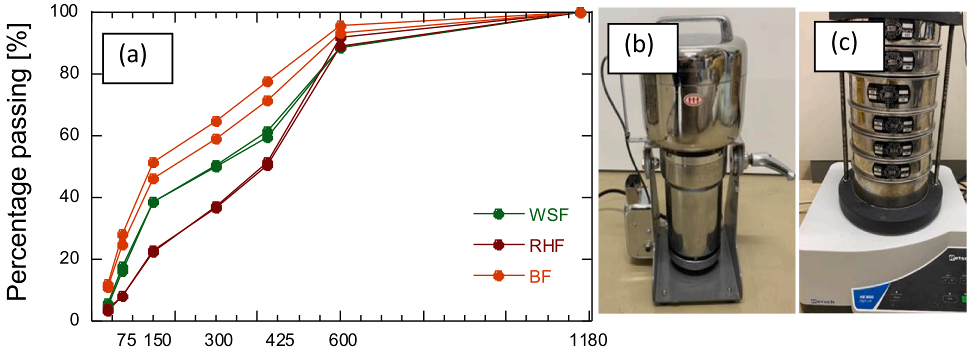


Fig. 5. Cellulosic fiber size identification process: a) particle size distribution, b) high-speed mill to crush fibers, and c) mechanical sieving machine (WSF: wheat straw fiber, RHF: rice husk fiber, BF: bamboo fiber).

information on the chemical composition of a substance, such as the presence of specific functional groups and their relative abundance, by analyzing the absorption patterns of functional groups in the sample [2,72]. In the analysis, the chemical composition and functional groups related to cellulose-based fibers are examined. Hence, the characteristic peaks of the cellulose-based fibers, mainly, the C-H and C-O stretching vibrations and the O-H bending vibrations, were identified and analyzed.

D) Microscopic and morphological characteristics

Expansive soils possess certain unique properties that can lead to significant volume changes due to the variation in moisture caused by the presence of clay minerals. The dominant components in the clay minerals in expansive soils are montmorillonite and kaolinite, followed by illite, quartz, and small fractions of other minerals. Montmorillonite-rich clay minerals are responsible for the swelling and shrinkage behavior of expansive soils [73,74]. Hence, using XRD/ X-ray diffraction and SEM/ EDS methods can reveal the formation of the soil matrix in terms of the mineralogical composition and morphology. These methods are particularly beneficial for mitigating the development of cracks due to drying and wetting cycles.

However, this research mainly focused on the morphological characteristics of stabilized soil. The interaction of the fibers with the soil can be seen from the SEM/EDX analysis. To analyze the SEM-EDX images, a JSM-7001F analytical thermal field emission instrument, with an advanced magnification system, was used. SEM provides high-resolution images of soil samples and detailed visual information on the soil structure, particle morphology, and distribution of stabilizers within the soil matrix [75,76]. The analysis was performed for the stabilized soil and untreated pseudo-expansive soil.

3. Results and discussions

In this section, the empirical analysis will be provided based on the obtained results from the study. All the primary/raw data obtained during the study will be presented. The results of untreated and cellulose-based fiber stabilized soils will be compared, and the discussion and interpretations of the results will be thoroughly presented. The effect of cellulose-based fiber on each improved engineering parameter will be discussed based on the optimized values obtained from the Taguchi method and ANOVA results analysis will be provided at the end of the results and discussions section.

4. Preliminary investigation of pseudo-expansive soil

The pseudo-expansive soil was an artificially replicated soil made from a combination of bentonite Kunigel V1, Kasaoka clay soil, and Tochi clay soil. The geophysical properties, Atterberg limits, and microstructural characteristics of the replicated soil were investigated as a preliminary study. This preliminary investigation showed that the characteristics of the replicated pseudo-expansive soil were similar to those of the original expansive soil in terms of the free swelling ratio and Atterberg limits. The geophysical properties of the pseudo-expansive soil are shown in Fig. 6 with respect to those of the original black cotton soil.

XRD analysis was conducted to investigate the microstructural traits of both the replicated expansive soil and the original expansive black cotton soil. The results revealed that montmorillonite, quartz, and kaolinite are the predominant mineral components in both soils, and these minerals play a pivotal role in the notable swelling behavior of the soil. Fig. 7 displays the mineral composition of these two soil types.

4.1. Preliminary investigation of cellulose-based fiber additives

Cellulose-based fibers have a wide range of properties that should be evaluated before they are used as potential soil stablizing material. The cellulose content, water absorption, and chemical composition of the cellulosic fibers are essential parameters for a preliminary investigation. The higher the cellulose content in the fibers, the higher the water absorption that is observed. This confirms that there is a correlation between the cellulose content and water absorption. The procedure to obtain the water absorption and cellulose content is briefly described in Section 2 (C). Fig. 8 shows the water absorption and its relationship to the cellulose content of the fiber materials.

It is also observed that the increase in time of absorbing water varies from one fiber to another. Rice husk fiber could quickly absorb the water and maintain a steady state of absorption whereas the bamboo and wheat straw fibers didn't exhibit maximum absorption capacity at shorter time intervals. Hence, this indicates that the quality of the fiber materials interacts with the soil particles at the time absorbing the excess amount of that eater from the soil.

The FTIR analysis also revealed the presence of cellulose chemical compounds in the fibers and the characteristic absorption bands associated with cellulose and the water-absorbing characteristics. It is helpful to identify the major functional groups and spectrums in the fibers. The FTIR analysis for cellulose-based additives is shown in Fig. 9. The bamboo fiber, shown in Fig. 9(a) has a typical high peak in the spectrum at 3343.55, which represents the cellulose group (-OH). This stretching peak indicates a high degree of both crystallinity and hydrogen bonding. It behaves similarly to the wheat straw fiber shown in Fig. 9(c). In addition, the CH group was

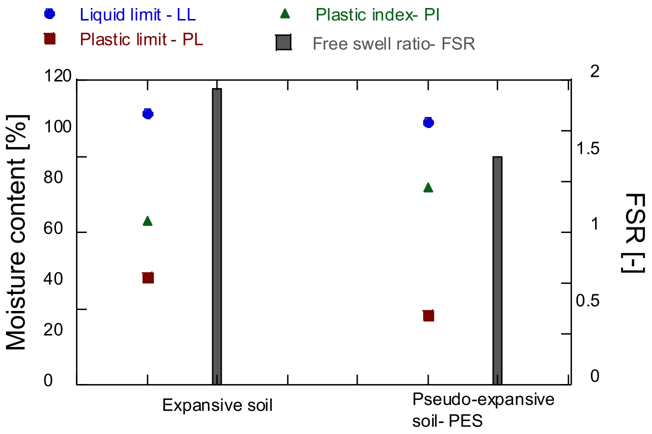


Fig. 6. Preliminary results for geophysical characteristics of the soil.

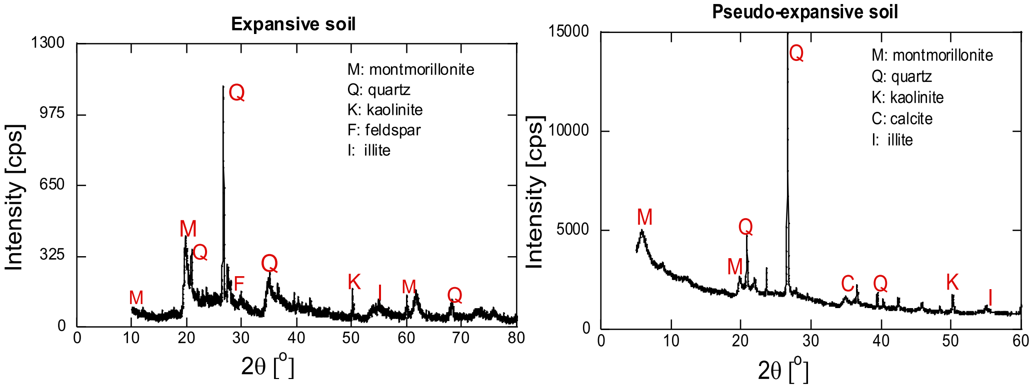


Fig. 7. Mineralogical analysis of both expansive black cotton soil and pseudo-expansive soil.

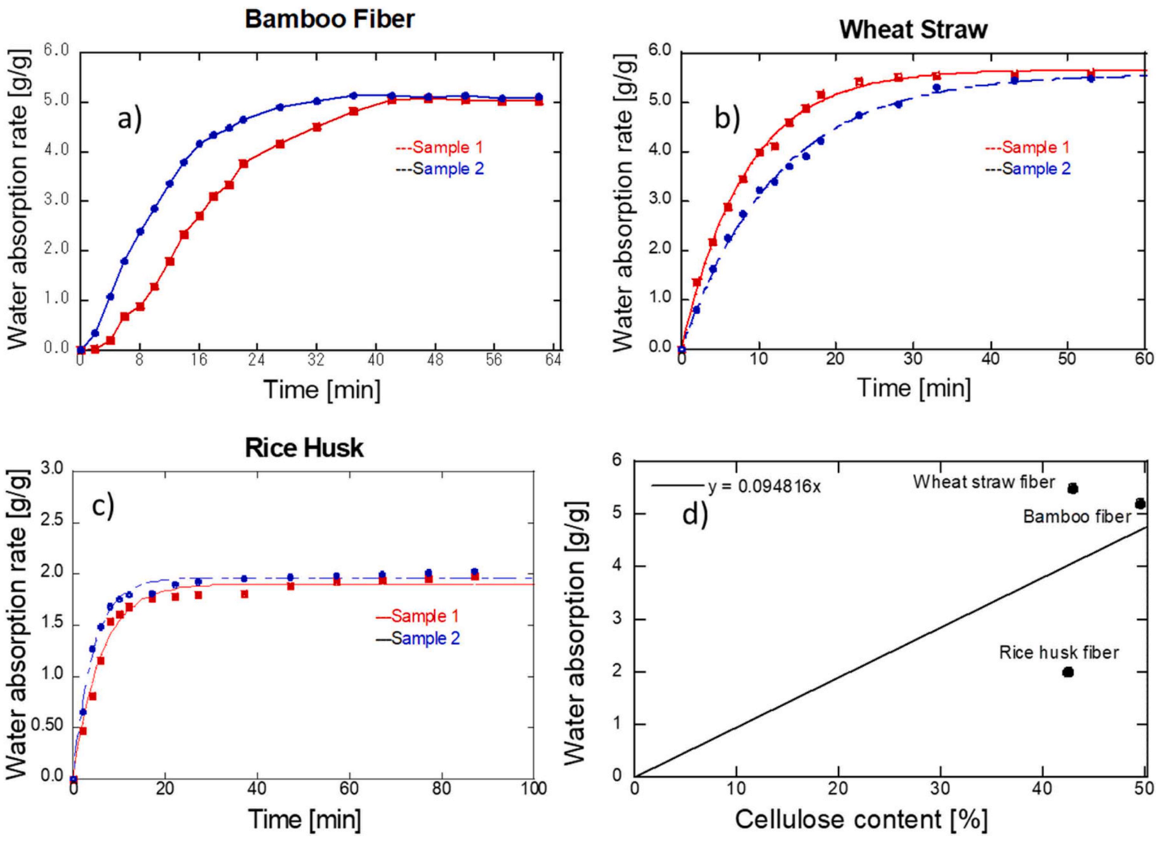


Fig. 8. Physical characteristics of cellulose-based fiber additives: a) bamboo fiber, b) wheat straw fiber, c) rice husk fiber, and d) relation of water absorption vs cellulose content.

observed at peaks of 2917.08 and 2917.55 for the bamboo and wheat straw fibers, respectively. This shows that carbon is a major component in cellulose materials. As seen in Fig. 9(b), rice husk fiber has a short and wide stretching peak at 3346.92. Cellulose is the main compound in the rice husk. OH, and CH were also found as functional groups of cellulose. This was also confirmed in the SEM-EDX analysis whose details are given in Figs. 18, 20, and 22 in Section 3.8. The spectrum of cellulose from the FTIR analysis shows that bamboo fiber and wheat straw fiber have high water-absorbing capacities.

4.2. Analysis of soil stabilized with cellulose-based fibers by the Taguchi method

The main purpose of using the Taguchi method was to design the experiment scientifically and to observe the objective factors, both

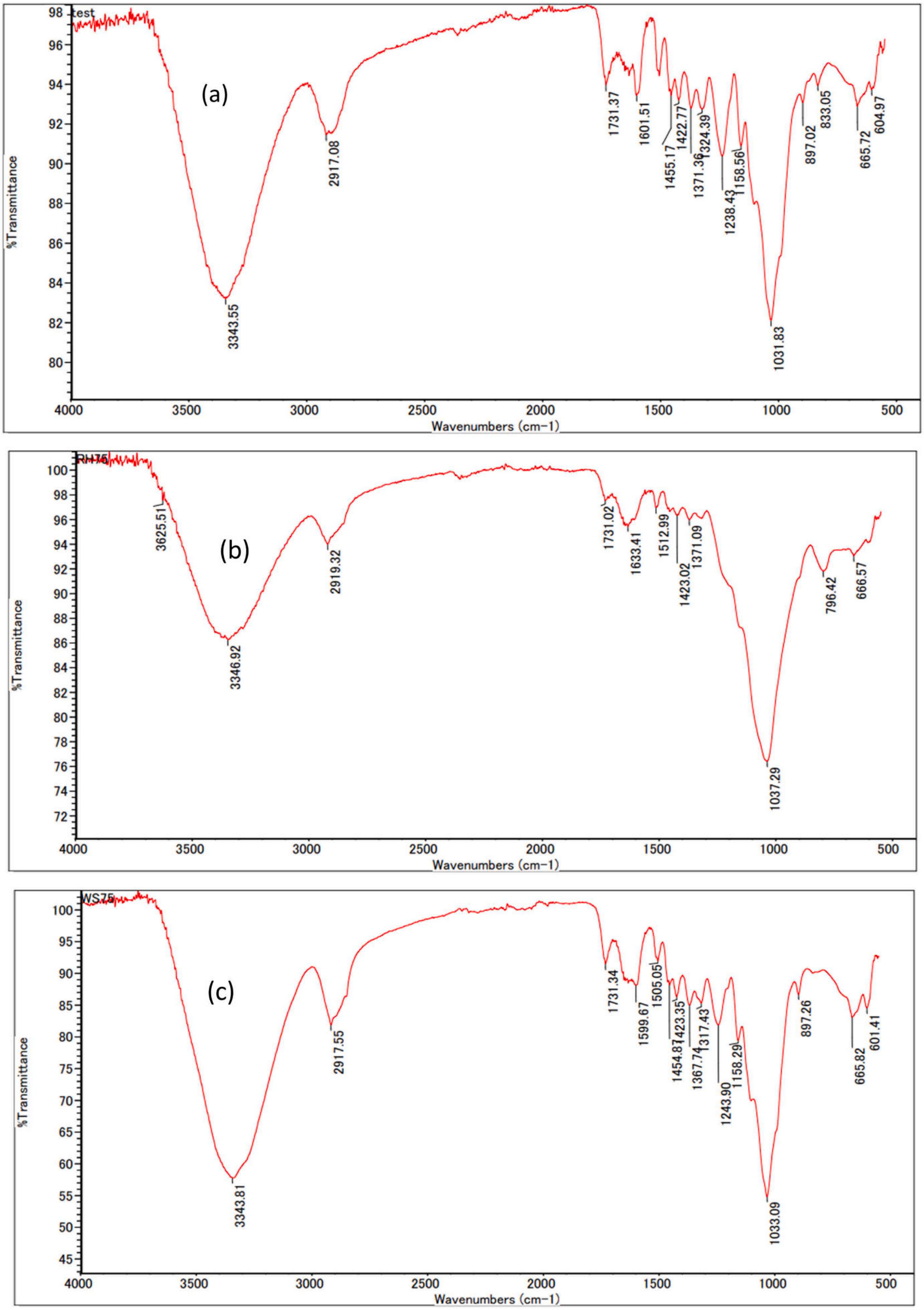


Fig. 9. FTIR analysis for cellulose-based fibers: a) bamboo fiber, b) rice husk fiber, and c) wheat straw fiber.

controllable and non-controllable, with the optimal effects in terms of maximizing the response factors and minimizing the noise factors [37,41]. The approach of the Taguchi method is suitable for these experimental conditions because it helps to carry out the experiments in a consistent manner under controlled conditions [77]. Taguchi uses multiple factors combined with appropriate levels of parameters to optimize the desired response. The detailed design matrix is described in Section 2, Table 3, and Table 4. Table 7 shows the results of tests for the multiple response factors that were obtained from the design of the experiments using the Taguchi method.

The results presented in Table 7 were obtained based on Table 3, given in Section 2.2. The results were analyzed to determine the optimum combinations with respect to the fiber content, fiber size, and other physical conditions of the fiber materials. Ikeagwuani et al. [47] discussed that Taguchi method mainly uses the signal-to-noise (S/N) ratio to obtain the optimized response factors considering various conditions. The S/N ratio should have different optimal mean values for each response factor, such as Atterberg values, FSR values, LS, and UCS values with respect to the fiber content, fiber size, or fiber materials. Hence, the objective responses for the S/N ratio are assumed to fall into three categories, namely, nominal is better, larger is better, and smaller is better. However, the target of this research is to maximize and minimize the response factors. Thus, the categories of larger is better and smaller is better were assumed[39,40]. The Minitab software analyzes the S/N ratio and mean values of the response factors under the following conditions.

$$\text{Larger is } \mathit{better} : \mathrm{S} - \mathrm{N} = -10\log\left(\frac{1}{n}\sum\nolimits_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{4}$$

$$\text{Smaller is } \mathit{better} : \mathrm{S} - \mathrm{N} = -10\log\left(\frac{1}{n}\sum\nolimits_{i=1}^{n}y^2\right) \tag{5}$$

5. Effect of cellulose-based fibers on Atterberg limit values

The effect of cellulose-based fibers on the Atterberg limits can vary due to several factors, including soil type, fiber characteristics (size and length), fiber dosage, testing methods, and other environmental conditions. The cellulose-based fiber content and fiber size have a significant effect on the improvement of stabilized soil. The effect of the cellulose-based fibers on the liquid limit and plastic index values of the stabilized expansive soil was evaluated by the Taguchi S/N ratio method. The improvement seen in the stabilized expansive soil was significant. Fig. 10 presents the Atterberg values obtained from the design of the experiment for the soil and cellulose-based additives.

Bamboo, rice husk, and wheat straw fibers were employed to assess their impact on soil stabilization, utilizing S/N ratio analysis as a benchmark. Notably, rice husk fiber, when applied in combinations of (15 %, 300 μm) and (5 %, 300 μm), demonstrated improvements in Plasticity Index (PI) and Liquid Limit (LL) values, respectively. Furthermore, its ability to react with the soil and promote densification makes it well-suited for enhancing soil consistency values [78–80]. Thus, for the liquid limit and plastic index, rice husk fiber with combinations of (5 %, 300 μm) is 64 % and (15 %, 300 μm) is 38 % respectively. Chen et al. [81] and Muntohar er al. [82] examined the rice husk stabilized soil and the results obtained were similar with this study.

According to a study by Sorsa et al.[83] and Kiflu et al.[84] in the majority of cases, materials with Plasticity Index (PI) values exceeding 30 % are deemed unsuitable for subgrade construction. In this study, the optimal conditions for PI improvement are indicated by higher S/N ratios were achieved with rice husk fibers at a dosage of 15 % and a size of 300 μm, as illustrated in Fig. 11. Furthermore, it is evident that a specific combination of fiber size and type significantly contributes to the enhancement of PI values [82,85]. For instance, the utilization of rice husk fibers at dosage of both 15 % and 5 %, each with a size of 300 μm, resulted in a notable improvement in both PI and Liquid Limit (LL) values. Specifically, LL values decreased from 103.4 % to 73 %, and PI values decreased

Table 7
Test results for multiple response factors (LL, PI, LS, FSR, and UCS).

Test ID	Cellulose-based fiber	Cellulose content, %	Fiber size, μm	LL, %	PI, %	LS, %	FSR%	USC, kPa
PES	-	0	0	103.4	77.7	78.3	1.94	109.5
1	BF	5	75	79.67	56.23	90.1	1.6	146.0
2	BF	10	150	76.80	52.24	95.8	1.6	206.9
3	BF	15	300	76.46	45.24	95.1	1.4	225.8
4	RHF	5	150	76.72	47.28	77.5	1.2	134.6
5	RHF	10	300	73.65	45.59	82.4	1.2	222.6
6	RHF	15	75	74.88	38.76	85.9	1.3	163.1
7	WSF	5	300	79.30	43.02	91.5	1.2	171.3
8	WSF	10	75	91.48	43.23	97.2	1.1	193.2
9	WSF	15	150	79.67	51.20	97.9	0.9	151.5

PES: pseudo-expansive soil, BF: bamboo fiber, RHF: rice husk fiber, WSF: wheat straw fiber

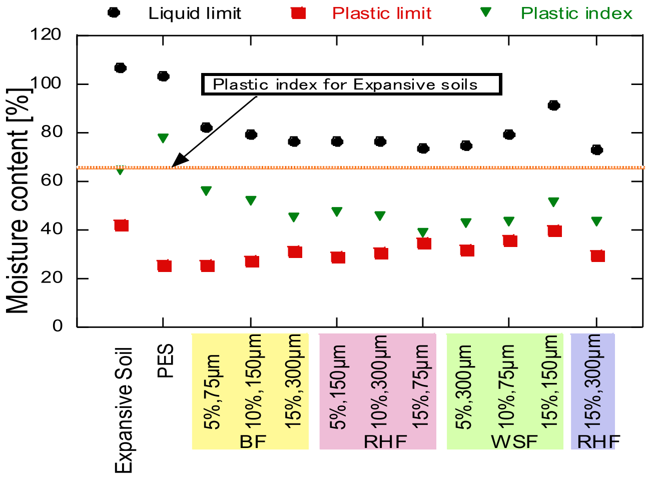


Fig. 10. Atterberg limit test results for soil stabilized with cellulose-based fibers.

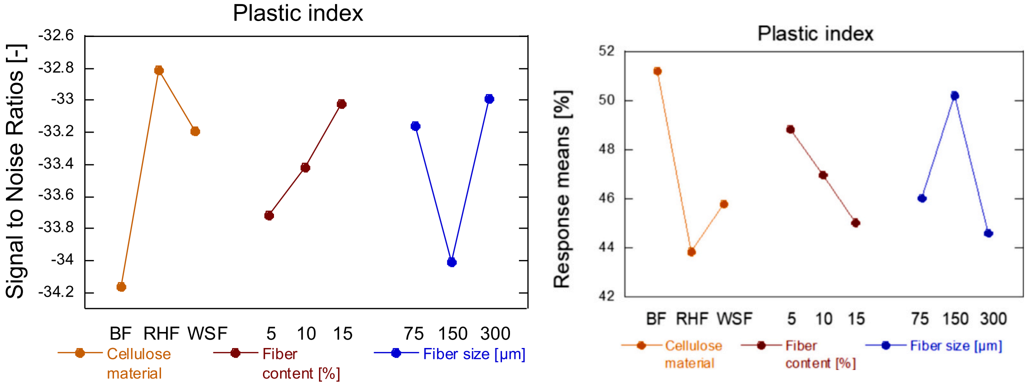


Fig. 11. Taguchi S/N ratio approach for response factor of PI.

from 80 % to 38 %.

5.1. Effect of cellulose-based fiber additives on FSR

Augmenting the wheat straw fiber content and size (15 %, 150 μm) resulted in a notable reduction in the free swell ratio of the stabilized soil as shown Fig. 12 of S/N ration analysis for FSR. Similarly, an increase in the cellulose fiber, namely, the bamboo fiber and rice husk fiber, also decreased the swelling index of the soil. However, the improvement seen for the other cellulosic fibers appears to be inconsistent. This is due to the nature of the cellulosic fibers and the characteristics of the soil [86]. Increasing the fiber content and fiber size leads to an increase in fiber surface area and produces erratic results. In some cases, the effect of the fibers in reducing the swelling ratio of the stabilized soil may be impaired because the fibers may be suspended separately in the water [87,88]. Looking at the bamboo conditions alone, settlement will certainly take place when the fiber size is large.

From the S/N ratio analysis shown in Fig. 12, the higher S/N ratio indicates the optimum condition for improving the free swelling ratio of the stabilized soil by wheat straw fiber (15 %, 150 μm). According to the S/N approach, the main factors contributing to the improvement of the stabilized soil are the fiber content and the type of fiber. Therefore, the swelling was relatively suppressed under the conditions of large particle sizes and higher additive contents [89]. The study conducted by Mishra et al. [88] says, the water-absorbing capacity of cellulose-based fibers has a direct effect on the swelling condition of the stabilized soil. Therefore, wheat straw fiber absorbed significant amounts of water and was used to control the swelling phenomenon of the soil. The wheat straw fiber improved the swelling behavior of the soil from 1.5 to 0.9, which means that the swelling potential of the stabilized soil was reduced by at least 45 %.

5.2. Effect of cellulose fiber additives on linear shrinkage characteristics

Linear shrinkage is one of the physical properties used to evaluate soil behavior under dry conditions. The shrinkage phenomenon of expansive soils is inevitable. To analyze the shrinkage behavior of cellulose-based stabilized soil, the experimental condition was

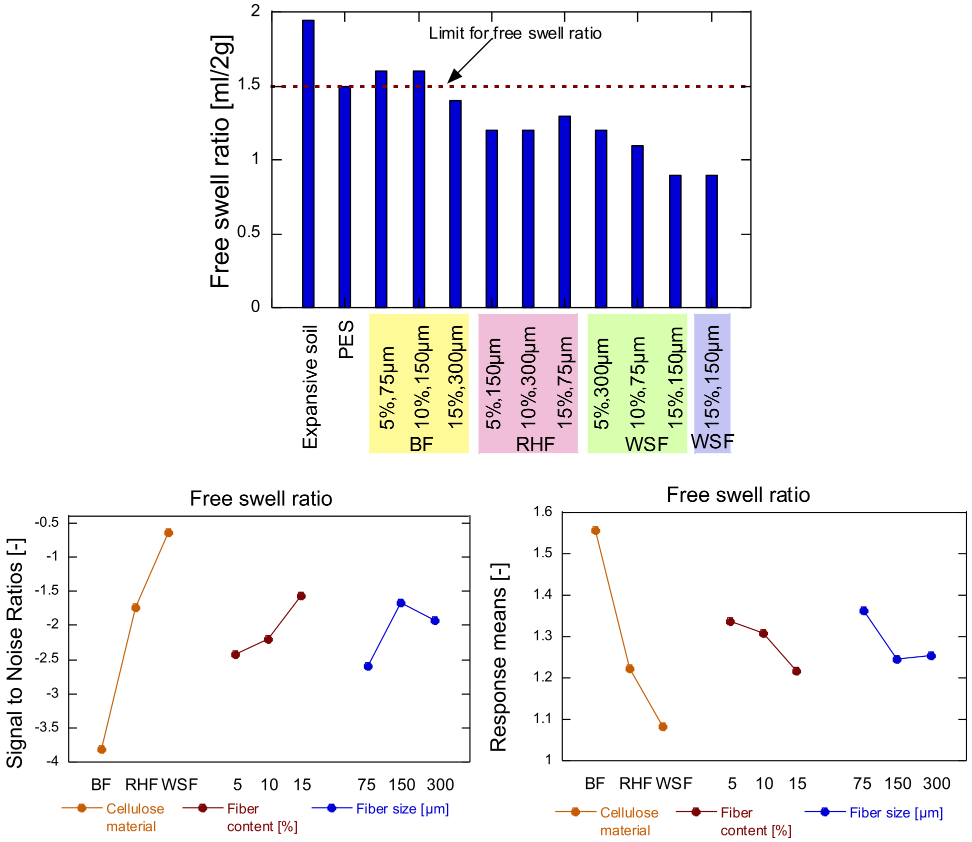


Fig. 12. Approach of S/N ratio analysis for free swell ratio of cellulose fiber-stabilized soil.

examined by the Taguchi method. The test results show that the linear shrinkage was improved by 75 % or more with all combinations, confirming that cellulose-based fibers have a suppressing effect on linear shrinkage. The results of the Taguchi method analysis show that the addition of wheat straw fiber (15 %, 75 µm) provided the largest reduction in linear shrinkage. Almost all cellulosic fiber additions changed the soil behavior with the designed combination of fiber content and fiber size. However, the optimum condition should be established from the combination of cellulose materials.

Minitab software was used to analyze experimental conditions. It is shown that wheat straw fiber (15 %, 75 µm) is an optimal cellulose-based fiber for effectively improving the shrinkage properties of stabilized soil. The soil stabilized with fiber additives shows similar results of reduction in shrinking and cracking behavior [10,13]. Fig. 13 shows that the cellulose-based fiber additions result in a decrease in shrinkage length. However, while the fiber material and fiber content greatly contribute to the improvement of the shrinkage behavior of stabilized soil, the fiber size contributes less to reducing the shrinkage. This phenomenon can be observed by analyzing the S/N ratio of the cellulose-based fiber additives with the corresponding response factors provided in Fig. 13.

6. Effect of cellulose-based fibers on UCS

The unconfined compressive strength test is used to measure the strength of the soil for resisting applied compressive loads. The UCS test helps to evaluate the strength of expansive soils and resist changes in volume due to changes in moisture content and associated stress. To evaluate the mechanical or strength performance of the stabilized soils, bamboo, rice husk, and wheat straw fibers were used in various combinations of fiber dose and fiber size. The improvement in the strength of the expansive soils stabilized with cellulose-based fibers could be attributed to the interaction and interlocking mechanism between the clay particles and the fibers. As the fiber content was increased, the strength development ceased, and the performance was significantly affected. The soil specimens freshly mixed with cellulose-based fibers developed higher strength at an earlier stage than those with a longer curing time. When a specimen was held for a longer curing time, the cellulose fibers absorbed the water from the specimen which contributed to the lower strength development. This is because the fibers, like cement, do not contribute to the hydration reaction that takes place in the soil.

The Taguchi method was also used to determine the experimental conditions and to analyze the optimal condition of the cellulose materials with respect to the UCS as a response factor. Based on this method, it is seen in Fig. 14 that bamboo fiber is more recommended for stabilizing expansive soils and achieving maximum strength than the other cellulose fibers. While the soil stabilized with rice husk and wheat straw fibers displayed inconsistent improvement with all combinations, the soil stabilized with bamboo fiber displayed greater improvement with all combinations. Moreover, a consistent improvement in the UCS values was observed in all cases

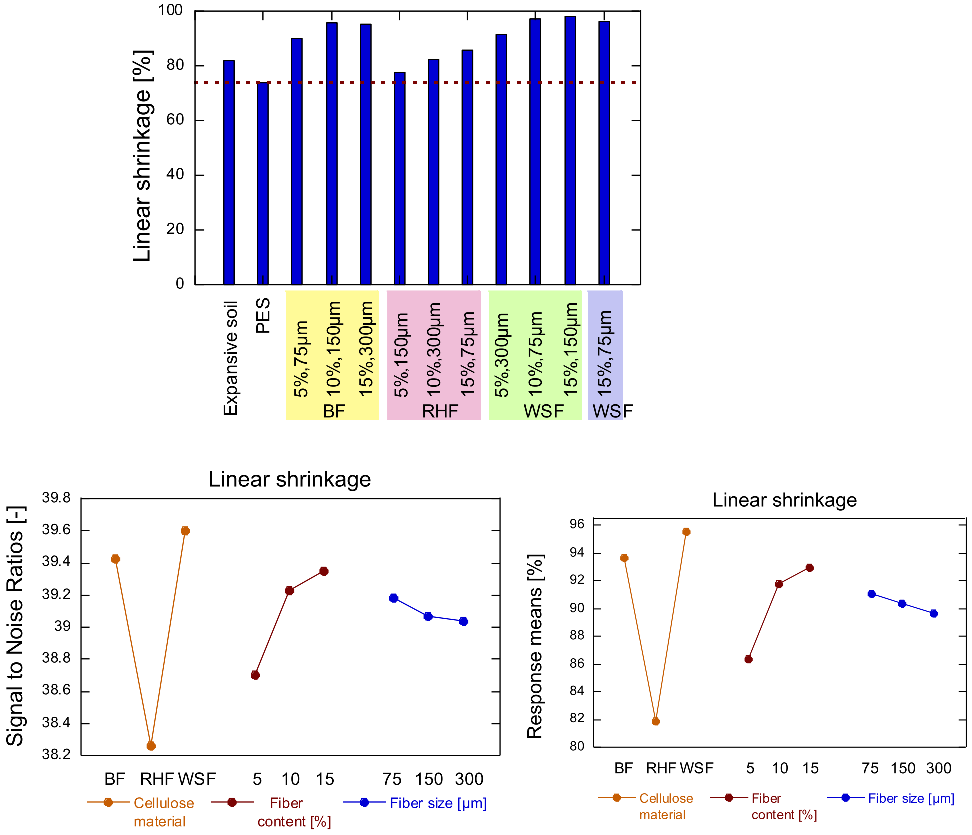


Fig. 13. Approach of S/N ratio or linear shrinkage of cellulose fiber-stabilized soil.

of the bamboo fiber-stabilized soil. Fig. 14 shows the results of the UCS values for various combinations of the soil stabilized with cellulose-based fibers.

The improvement in the UCS value by 15 % with 300 µm of the soil stabilized with the bamboo fiber was investigated for 0, 7, and 28 days of curing, and the results obtained were 222.8 kPa, 345.3 kPa, and 274.7 kPa, respectively. The maximum stress for the expansive soil without cellulose-based fiber additives was 105.8 kPa. This indicates that the cellulose-based fiber additives improved the mechanical performance of the stabilized soil 100 % more than that of the non-stabilized expansive soil. In addition, regardless of

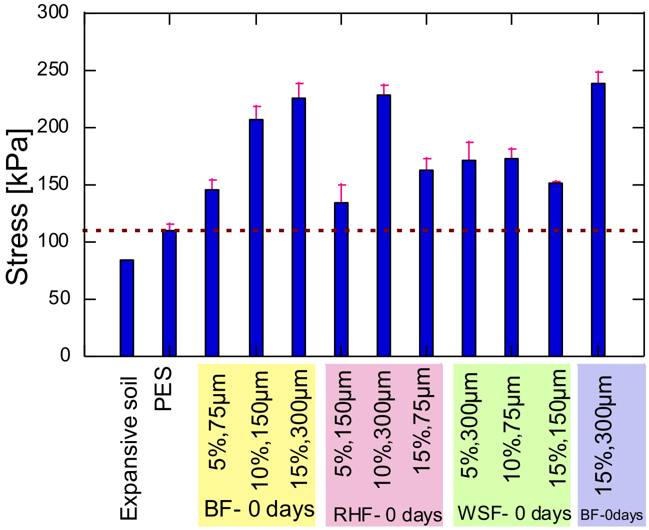


Fig. 14. UCS values for cellulose-based fiber-stabilized soil and non-stabilized soil.

the type of cellulose fiber, the fiber content and fiber size were closely related to the strength development of the stabilized soil. In Fig. 15, the data show that the UCS value for the 7-day curing day is higher than that for the 28-day cure days. Perhaps the maximum strength development had already been achieved before reaching 28 days of curing. This is because there were no cementing or hydration properties in the fiber that could have contributed to the development of strength in the stabilized soil during the longer curing time.

On the other hand, cellulose fibers may improve the cohesion of the soil matrix by providing additional interlocking and bridging effects. The addition of more fibers increases cohesion and contributes to the UCS value. This makes the soil more resistant to deformation and shear failure, as shown by the results in Fig. 15.

6.1. Statistical analysis: ANOVA approach

The ANOVA analysis of cellulose-based additive-stabilized soil demonstrated notable distinctions among the tested groups from a statistical perspective. The factors examined, such as the type and quantity of cellulose-based additives, exerted substantial impacts on the properties of the stabilized soil. Specifically, the type of cellulose-based additive emerged as a significant determinant influencing key soil characteristics, including the Plasticity Index (PI), Free Swell Index (FSR), and Linear Shrinkage (LS), with varying effects observed in relation to rice husk and wheat straw. The incorporation of different types of cellulose-based additives led to varying degrees of enhancement in these properties, underscoring their effectiveness in altering soil behavior[90,91]. Additionally, the content/dosage of cellulose-based additives was identified as another influential factor influencing the soil's mechanical properties, particularly in terms of strength-related factors like the Unconfined Compressive Strength (UCS).

This phenomenon was similarly observed in studies conducted by Son et al. [92] and Baek et al. [93] thereby affirming the significant impact of additive content or dosage on strength-related parameters. Noteworthy variations in soil properties were evident with varying additive content, emphasizing the pivotal role that cellulose additive content plays in achieving the desired outcomes in soil stabilization [92,93]. Thus, to comprehensively analyze the variance results, a regression analysis model was employed for experiments conducted using the Taguchi orthogonal array analysis [47]. Efforts were made to formulate regression models for the Plastic Index (PI) (Eq. 4), Free Swell Index (FSR) (Eq. 5), Linear Shrinkage (LS) (Eq. 6), and Unconfined Compressive Strength (UCS) (Eq. 7) values using the Minitab statistical software. The regression model achieved a 95 % confidence level (with the predictor P-value being less than 0.05). Confirmatory tests were also conducted for individual response parameters based on the results derived from the Taguchi method, and no significant disparities were identified between the tested runs and the outcomes generated by the model. Therefore, when the equation was formulated, BF represented bamboo fiber, RHF represented rice husk fiber, and WSF represented wheat straw fiber.

Regression Equation.

$$\text{PI}=46{\cdot}98+4{\cdot}26@\text{BF}-3{\cdot}10\,@\text{RHF}-1{\cdot}16\,@\text{WSF}+1{\cdot}87\,@\,\%\_5+0{\cdot}04\,@\,\%\_10-1{\cdot}91\,@\%\_15-0{\cdot}90\,@\mu\text{m}\_75+3{\cdot}26\,@\mu\text{m}\_150-2{\cdot}36\,@\mu\text{m}\_300 \tag{4}$$

$$\text{LS}=90{\cdot}378+3{\cdot}289\,@\text{BF}-8{\cdot}444\,@\text{RHF}+5{\cdot}156\,@\text{WSF}-4{\cdot}011\,@\,\%\_5+1{\cdot}422\,@\,\%\_10+2{\cdot}@\,\%\_15+0{\cdot}689\,@\mu\text{m}\_75+0{\cdot}022\,@\mu\text{m}\_150-0{\cdot}711\,@\mu\text{m}\_300 \tag{5}$$

$$\text{FSR}=1{\cdot}2778+0{\cdot}2556\,@\text{BF}-0{\cdot}0444\,@\text{RHF}-0{\cdot}2111\,@\text{WSF}+0{\cdot}0556\,@\,\%\_5+0{\cdot}0222\,@\,\%\_10-0{\cdot}0778\,@\,\%\_15+0{\cdot}0556\,@,\mu\text{m}\_75-0{\cdot}0444\,@,\mu\text{m}\_150-0{\cdot}0111\,@,\mu\text{m}\_300 \tag{6}$$

$$\text{UCS}=179{\cdot}44+13{\cdot}46\,@\_\text{BF}-6{\cdot}01\,@\_\text{RHF}-7{\cdot}44\,@\_\text{WSF}-28{\cdot}81\,@,\%\_5+28{\cdot}12\,@,\%\_10+0{\cdot}69\,@,\%\_15-12{\cdot}01\,@,\mu\text{m}\_75-15{\cdot}11\,@,\mu\text{m}\_150+27{\cdot}12\,@,\mu\text{m}\_300 \tag{7}$$

The statistical outcomes of the variance analysis for the response parameters, as computed from the equations mentioned earlier, are presented in Tables 8 to 11. *Table 8* , in particular, centers its analysis on two aspects: the contributing factor (percent contribution) and the P-values associated with the Plasticity Index (PI) as a response parameter. Consequently, it is evident that the fiber's

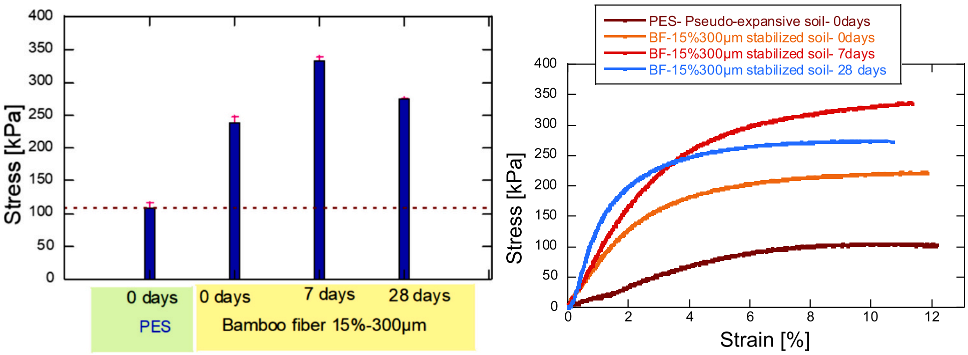


Fig. 15. Stress-strain relation and corresponding UCS values for soil stabilized with cellulose fiber.

contribution has a more pronounced impact on PI values compared to both fiber content and fiber size. Notably, rice husk fiber made a substantial contribution of approximately 37.41 % towards reducing the PI, bringing it down from 78 % to 38 %.

Likewise, as shown in Table 9, the ANOVA analysis underscores the pivotal role of fiber contribution, accounting for approximately 80.75 % of the reduction in the free swell ratio. In this context, wheat straw fiber demonstrates its effectiveness in diminishing the swelling potential from 1.64 g/ml to 0.9 g/ml. Furthermore, the significance of the P-values is worth noting. Choi et al.'s study [91] emphasizes that P-values less than 0.05 are indicative of greater significance. However, it's important to note that the marginal difference in P-values here does not alter the conclusion, affirming that fiber contribution stands out as a crucial factor in the enhancement process.

The ANOVA analysis of the linear shrinkage test results reveals that the most substantial contributing factor is the fiber type, accounting for approximately 80.38 % of the observed variance, as indicated in Table 10. Moreover, the associated P-values of 0.007 further underscore this significance. This underscores the influential role of the characteristics specific to wheat straw fiber in mitigating soil shrinkage by effectively bridging the gap between the fiber and soil particles. A study conducted by Meena et al. [94] comprehensively assessed the influence of wheat straw on enhancing various geotechnical properties of the soil. The findings of this study convincingly establish that wheat straw material exerts a noteworthy impact on altering soil behavior, encompassing both physical and strength-related parameters.

Conversely, when it comes to enhancing the strength parameter, the most influential factor is the content of cellulose fibers. The ANOVA results, displayed in Table 11, highlight that bamboo fiber content, in particular, makes a substantial contribution, accounting for approximately 52.88 % of the observed variance in Unconfined Compressive Strength (UCS) values. Additionally, the low P-value of 0.038 emphasizes the high level of confidence in this contribution's significance. Notably, unlike other cellulose-based additives, the presence of cellulose fibers significantly enhances the UCS values, increasing them from 109 kPa to 226 kPa, representing a remarkable improvement exceeding 100 %. Son et al. [92] and Baek et al. [93] both found that the content of additives significantly contributed to the enhanced compressive strength of the soil.

Furthermore, the model equations created for interpreting the ANOVA results are closely tied to the significance of the test methods used in data generation. The ANOVA analysis plays a pivotal role in confirming the reliability and uniformity of the test results, the experimental approaches utilized, and the relevance of these outcomes with respect to response variables and influential factors[43,92].

7. Effect on microstructural and microscopic characteristics

The effects of cellulose-based fibers on the microstructural and morphological characteristics of stabilized soil should be investigated by XRD and SEM analysis. It is a fact that the addition of cellulose fibers can alter the soil fabric by modifying its particle arrangement and distribution. The arrangement of particles promotes the formation of bonds and improves the structure of the soil [51,95,96]. An analysis of the mineralogical composition by XRD of the pseudo-expansive soil is discussed in Section 3.1 of Results and Discussions. In this study, to assess the fiber interaction with the pseudo-expansive soil, pseudo-expansive soil containing 15 % of each of the cellulose-based fibers with a particle diameter of 300 μm was examined using scanning microscopy (SEM-EDX). Several images and points of analysis were taken into consideration during the experiment. As a result, Si, Al, Fe, and Mg were identified as the main elements in the pseudo-expansive soil at points 1 and 2 in Fig. 17. Some pore spaces were also seen in the SEM images for the pseudo-expansive soil shown in Fig. 16. The analysis was continued for the cellulose-based stabilized soil, first with bamboo fiber, then rice husk, and finally with wheat straw fiber, respectively. Furthermore, liquid nitrogen was used for elemental analysis by EDX and for cooling the detector, which is why a large amount of N was detected at 0.4 keV, as observed in all the EDX analyses.

The pseudo-expansive soil stabilized with bamboo fiber showed that the soil was homogenized with fiber and formed strong bonds. Fig. 18 shows that the observation results from the soil stabilized with bamboo fiber and the pseudo-expansive soil adhered to the periphery of the bamboo fiber. An EDX analysis was performed on the bamboo and the region where the pseudo-expansive is thought to have adhered, confirming that the pseudo-expansive soil had adhered to the bamboo fiber. C, O, Si, and Al are found primarily at points 1 and 2, whereas C and O are the major constituents of the plant shown in Fig. 19. Hence, C and O are constituents of cellulose ($C_6H_{10}O5$), which is the main component of plants, and therefore, are believed to have been caused by the addition of bamboo. The results indicate that the pseudo-expansive soil was uniformly mixed with bamboo. However, a slight roughness on the surface of the stabilized soil was observed due to the roughness property of the bamboo fiber.

Fig. 20 shows the results for the pseudo-expansive soil with 15 % rice husk particles with a diameter of 300 μm. When compared to the bamboo fiber, it is concluded that the rice husk fiber was completely covered with pseudo-expansive soil. It was difficult to observe and differentiate the soil stabilized with the rice husk fiber from the pseudo-expansive soil. However, an EDX analysis was conducted on the soil stabilized with the rice husk fiber, and the main elements were identified as C, O, Si, and Al at points 1 and 2, as they were for the bamboo fiber. As shown in Figs. 20 and 21, wormlike shell structures were observed due to the characteristics of the rice husk fiber.

Finally, an EDX analysis was carried out on the soil stabilized with wheat straw. The results show that 15 % wheat straw fiber with a fiber size of 300 μm was firmly attached to the soil. In Fig. 22, a large amount of element C, which is a major component of cellulose, was observed. At point 1 in Fig. 23, a significant amount of Si was also observed in the detection process. Si, Al, and O, which are the main elements of the pseudo-expansive soil, were also detected at point 2. Uniform binding and fiber interaction were observed on the wheat straw-stabilized soil shown in Figs. 22 and 23. This is confirmation that wheat straw fiber can be an ideal sustainable material for the stabilization of weak soils. For the other cellulose fiber-stabilized soil, the same conclusion can be drawn. It is important to understand that bamboo and wheat straw fibers have similar properties and chemical compositions in many aspects, unlike rice husk

Table 8
Results of ANOVA for Plastic index (PI) Values.

Source	DF	Percent Contribution	Adj SS	Adj MS	F-Value	P-Value
Cellulose fiber	2	37.41 %	87.31	43.65	1.19	0.457
Fiber content, %	2	9.17 %	21.40	10.70	0.29	0.775
Fiber size,µm	2	21.90 %	51.10	25.55	0.69	0.590
Error	2	31.53 %	73.58	36.79		
Total	8	100.00 %				

Table 9
Results of ANOVA for Free Swell Ratio (FSR).

Source	DF	Percent Contribution	Adj SS	Adj MS	F-Value	P-Value
Cellulose fiber	2	80.75 %	0.336	0.178	9.44	0.096
Fiber content, %	2	6.95 %	0.029	0.014	0.81	0.552
Fiber size,µm	2	3.74 %	0.016	0.008	0.44	0.696
Error	2	8.56 %	0.036	0.018		
Total	8	100.00 %				

Table 10
Results of ANOVA for Linear shrinkage (LS) values.

Source	DF	Percent Contribution	Adj SS	Adj MS	F-Value	P-Value
Cellulose fiber	2	80.38 %	326.116	163.058	148.53	0.007
Fiber content, %	2	18.35 %	74.442	37.221	33.91	0.029
Fiber size,µm	2	0.73 %	2.942	1.471	1.34	0.427
Error	2	0.54 %	2.196	1.098		
Total	8	100.00 %				

Table 11
Results of ANOVA for Unconfined Compressive strength (UCS) values.

Source	DF	Percent Contribution	Adj SS	Adj MS	F-Value	P-Value
Cellulose fiber	2	8.89 %	817.8	408.91	4.27	0.190
Fiber content, %	2	52.88 %	4864.2	2432.12	25.41	0.038
Fiber size,µm	2	36.14 %	3324.7	1662.34	17.37	0.054
Error	2	2.08 %	191.4	95.72		
Total	8	100.00 %				

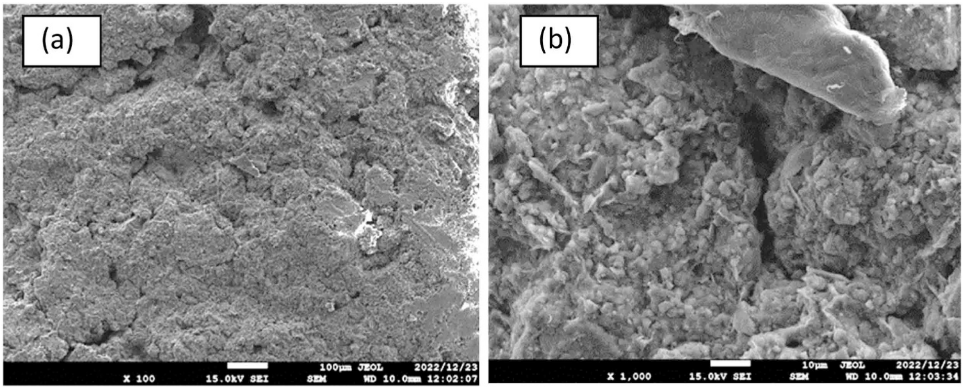


Fig. 16. SEM-EDX analysis for pseudo-expansive soil: (a) x100 and (b) x1000.

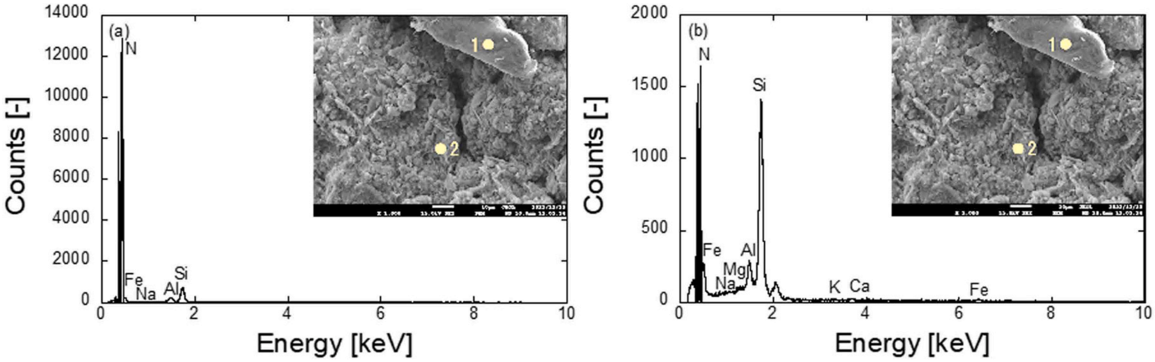


Fig. 17. EDX detection points for pseudo-expansive soil a) point 1 and b) point 2 at x1000.

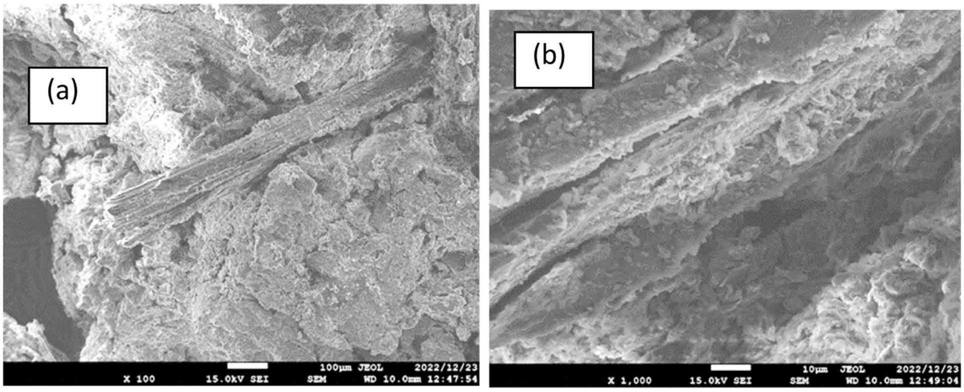


Fig. 18. SEM-EDX analysis for soil stabilized with bamboo fiber: (a) x100 and (b) x1000.

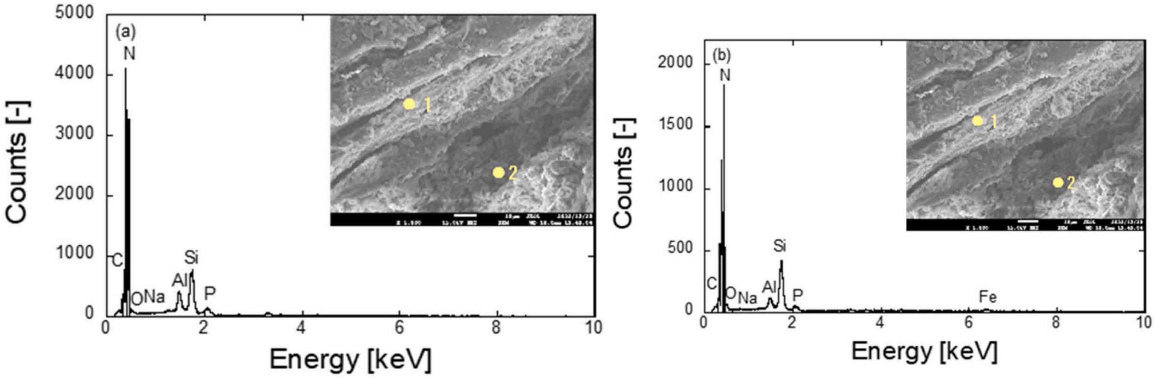


Fig. 19. EDX detection points for a) point 1 and b) point 2 at x1000.

fiber. These findings were also revealed by the FTIR analysis of the cellulosic fiber materials discussed in Section 3.2 and Fig. 9a-c.

8. Conclusion

In this study, the use of cellulose-based fiber additives to stabilize expansive soils, as investigated by the Taguchi method, has provided significant insights and practical applications. Through systematic experimentation and thorough analysis, this study has highlighted critical factors and their interactions in the improvement of geotechnical and mechanical characteristics of stabilized soil. Our findings highlight and conclude with the following crucial outcomes:

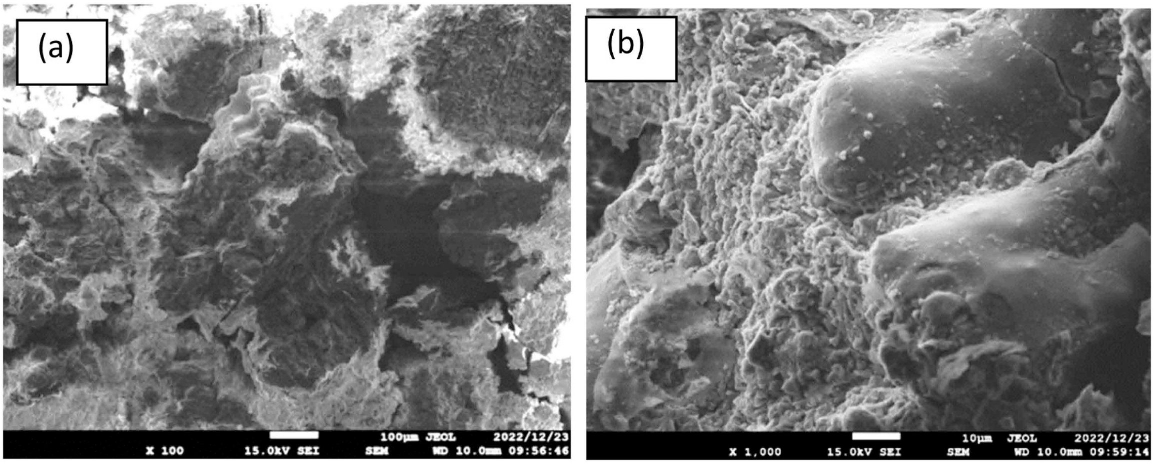


Fig. 20. SEM-EDX analysis for soil stabilized with rice husk fiber (RHF): (a) x100 and (b) x1000.

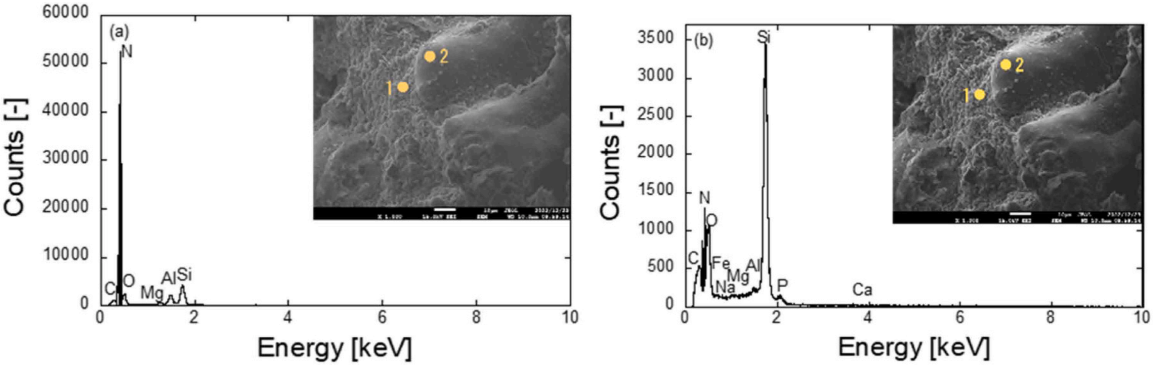


Fig. 21. EDX detection points for rice husk fiber at a) point 1 and b) point 2 at x1000.

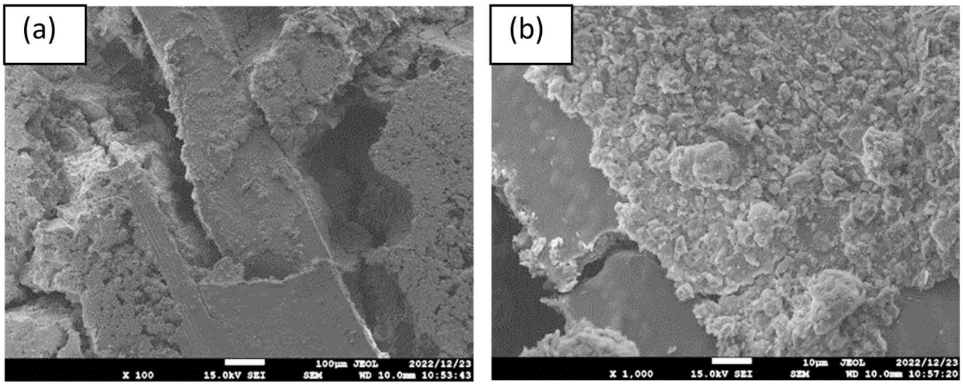


Fig. 22. SEM-EDX analysis for soil stabilized with wheat straw (WSF): (a) x100 and (b) x1000.

I. **Optimization of cellulose fiber content and size**:

Using the Taguchi method, we have identified the optimal combination of fiber content and size for effective soil stabilization. Specifically, the incorporation of wheat straw fibers at a concentration of 15 % and a size of 150 μm has proven to be the most favorable configuration, significantly reducing the free swelling ratio of the expansive soil, addition of rice husk fiber (15 %, 300 μm) reduced the PI values and bamboo fiber (15 %, 300 μm) increase the UCS values from 116Kpa to 222kPa.

II. **The effect of the cellulose-based fibers:**

The effect of additives on stabilized soil is observed in different aspects. In the process of soil stabilization, some cellulose

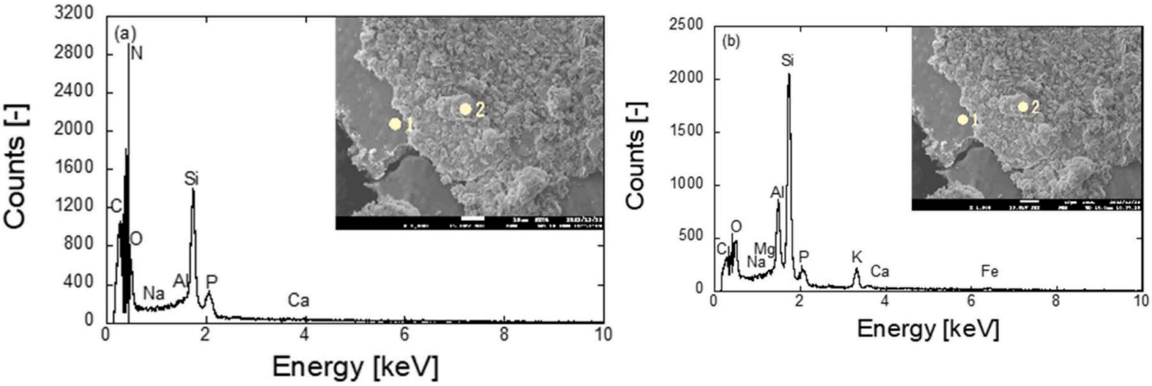


Fig. 23. EDX detection points for wheat straw fiber at a) point 1 and b) point 2 at x1000.

fibers are very effective because of its characteristics, some might have been influenced by the larger content and some effects have been seen due to the size of the additive materials. Therefore, these findings suggest that engineers and researchers can choose from a variety of cellulose-based fiber options, depending on availability and project-specific requirements.

III. **Engineering Applications and Environmental Considerations**:

The results of this study have significant implications for a wide variety of engineering applications. The ANOVA results reinforce the practical significance of incorporating these additives in geotechnical projects, including those involving road construction, foundations, and retaining structures. The use of the Taguchi method for the optimization of these additives in a practical setting can pave the way for cost-effective and reliable solutions. Moreover, the environmentally friendly nature of cellulose-based fiber additives, combined with their proven effectiveness in soil stabilization, holds great promise for sustainable engineering practices.

IV. **Future study directions**:

Future research can address long-term performance evaluations, durability studies, and a wider range of soil types and conditions to further improve the understanding of and practical application of cellulose-based fiber additives. In addition, the consideration of other influencing factors, such as climatic variations, may help to refine the application of these additives.

Finally, integrating ANOVA results with the Taguchi method increases our confidence in the effectiveness of cellulose-based fiber additives for stabilizing expansive soils. This research contributes to the advancement of geotechnical engineering practice by providing statistically validated solutions to the challenges associated with expansive soils in construction and infrastructure projects. It is our hope that these findings will inspire and inform future research and practical applications in the field.

CRediT authorship contribution statement

KINOSHITA Naoki: Funding acquisition, Project administration, Visualization. **GIDEBO Frehaileab Admasu:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **YASUHARA Hideaki:** Conceptualization, Data curation, Funding acquisition, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data Availability

Data will be made available on request.

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