Using Sisal Fibers for Improving Soil Properties

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Abstract

Shear strength is a critical factor in geotechnical engineering, influencing the stability of foundations, excavations, and slopes. This study explores the potential of sisal fibers as a sustainable and cost-effective reinforcement for soil stabilization. An experimental approach was adopted, incorporating varying percentages of sisal fibers into soil samples. Instead of conventional shear strength tests such as direct shear or triaxial testing, an alternative procedure was utilized to estimate soil shear strength based on compaction characteristics, deformation behavior, and cohesion improvements. The results indicate that sisal fiber inclusion enhances soil stability and crack resistance, with an optimal fiber content of approximately 5–10%. However, the absence of direct shear strength measurements presents a limitation, and further validation through standard shear testing is recommended. Despite this constraint, the study highlights sisal fiber reinforcement as an eco-friendly alternative for improving soil properties, particularly in resource-limited regions.

Keywords: Shear strength, sisal fiber, soil stabilization, unconfined test, sustainable construction

1. Introduction

Sisal fiber, derived from the Agave sisalana plant, is a natural and renewable material widely cultivated in regions such as Mexico, East Africa, Brazil, Haiti, India, and Indonesia (Saxena et al., 2011). The plant, characterized by sword-shaped leaves, grows to approximately 1 meter in height and 28 mm in width, containing 200-250 leaves (Rowell, 2008). Each leaf comprises about 1,000 fiber bundles, of which only 4% are utilized as fibers (Mishra et al., 2004). Historically, sisal fiber has been used for manufacturing ropes, mats, and twine due to its strength, durability, and resistance to environmental factors such as saline water and ultraviolet rays. Recently, it has become a familiar material for stabilizing soil in geotechnical and civil engineering applications. Weak or expansive soils rarely present building problems because of their properties of settlement and deformation under loading conditions though (Jones and Jefferson, 2012). Currently, traditional soil stabilization techniques are usually expensive and ecologically hazardous with the use of synthetic ingredients. As a result, there is a need for such affordable and sustainable substitutes. In particular, sisal fiber presents a possible solution. The main objective of this study is to determine how effective sisal fiber can be used as a reinforcing material that leads to an increase in soil stability. The specific goal of the study is to evaluate soil settling and deformation under load so that constructions can have a secure base. The research also seeks to strengthen the soil by adding sisal fiber, which may help to improve load distribution and increase the soil's load bearing capacity. Sisal, as a natural fiber provides support in strength, and encourages sustainable attitudes that aid soil stability. Many studies point to the possibility of sisal fiber for stabilizing soil. Studies demonstrate their efficacy as a sustainable binder for improving soil stability and shear strength. R.S. Panwar (2018) gave the economic feasibility of sisal fiber in conjunction with fly ash while Y. Wung (2014) prove improved shear strength using sisal fiber by supplying better cohesion. Furthermore, (Sani et al., 2017) and (Rana and Sonthwal) state that the treated sisal fiber containing rice husk ash can be utilized in

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infrastructure projects to enhance soil cohesion and slope stability. (Hejazi et al., 2012) highlight, that fiber length and composition are of critical importance for optimal performance, but that there are limits at which performance decreases. The adaptability and use of sisal fiber in geotechnical applications are demonstrated by the findings. An experimental research technique is used to determine how sisal fiber affects soil quality. Investigation was made with samples of varying quality soils collected, as well as with decorticated, processed sisal fibre from the same source. To characterize the soil, standard geotechnical tests are used to measure the soil's cohesiveness, compaction, and shear strength. The interest in this study is that it is an economical and sustainable approach to soil problems in expansive and weak soils. Sisal fiber's natural, renewable, and biodegradable properties provide a fit for international efforts to promote ecologically responsible building practices. Improving soil strength, cohesiveness, and load-bearing ability make projects safer and last longer.

2. Literature Review

Especially for soils, natural fibers (such as sisal) have been a groundbreaking material to stabilize, offering long-lived, efficient reinforcement. It helps in increasing soil strength, improving slope stability, and reducing soil collapse thus encouraging doing effective use of natural resources. Acetic acid and NaOH-treated sisal fiber results in improved mechanical qualities and durability that make them applicable for geotechnical applications such as infrastructure projects, road building, and slope stabilization.

Research supports the use of sisal fibers in improving soil qualities. (Wu et al., 2014) demonstrated that the shear strength of the silty clay reinforced by sisal fibers is increased. According to (Tiwari et al., 2021), state that sisal fiber and fly ash together economically viable for expansive soils. (Kafodya, 2019), argue that sisal fibers and rice husk ash increased cohesion, permeability, and slope stability significantly which makes them a good building material for roads and other infrastructure needs.

The ideal fiber length and content are required to achieve the desired effects. Research by (Pradhan et al., 2012), shows that shear strength and cohesiveness increase with increasing fiber length and content at least to some extent. Yet performance falls below 20 mm in length and 0.75% fiber, due to poor soil particle interlocking and decreased soil density. (Kafodya, 2019), state that highest cohesion values of 66 kPa were shown to be greater than those obtained for unreinforced soil of 18 kPa, demonstrating that the sisal fiber-reinforced soil was also effective. Fibers formed from sisal are biodegradable but chemical treatment can improve their durability. Environmental factors such as soil conditions, air humidity, and harvesting methods affect fiber quality and hence need comprehensive data to perform statistical analysis correctly.

The idea of fiber reinforcement is born from ancient natural processes, e.g. the movement of tree roots or animal structures, and whenever technologies that require fiber reinforcement are in relatively undeveloped states of the art, successive generations will frequently leverage the knowledge of these ancient natural processes (Kafodya, 2019). These methods, which have been modified by recent studies, considerably increase the permeability, shear strength, and bearing capacity of soil (Ghasabkolaei et al., 2017). Sisal fibers as cheaper and ecological improvement for meting soil performance in order to develop sustainable geotechnical engineering (Medina-Martinez et al., 2022).

*Figure **Error! No text of specified style in document.**-1 Sisal Fiber*

*Figure **Error! No text of specified style in document.**-2 Soil Mixed with Sisal Fiber*

3. Research Methodology

This section explores the materials used for soil improvement, focusing primarily on soil and natural composite materials like sisal fiber. It outlines the procedures for generating samples in accordance with the USCS soil classification system and details the testing methods for soil analysis.

3.1 Soil Selection

Depending on the location, the soil is made up of natural resources such as clay, silt, sand, or gravel and serves as a foundation for construction. Natural soil with low bearing capacity can be improved by adding stabilizers (such as cement or lime), using geosynthetics, or employing beneficial construction methods. Compaction, CBR, and plate load tests are performed during the design and construction stages to guarantee soil appropriateness and efficiency for the intended project. Soil is important for all infrastructure projects because of the changes that occur during construction and the duration of life. So, site preparation, loading distribution and drainage management, and soil improvement procedures must be carried out in a correct manner to ensure that a structure lasts and is useful.

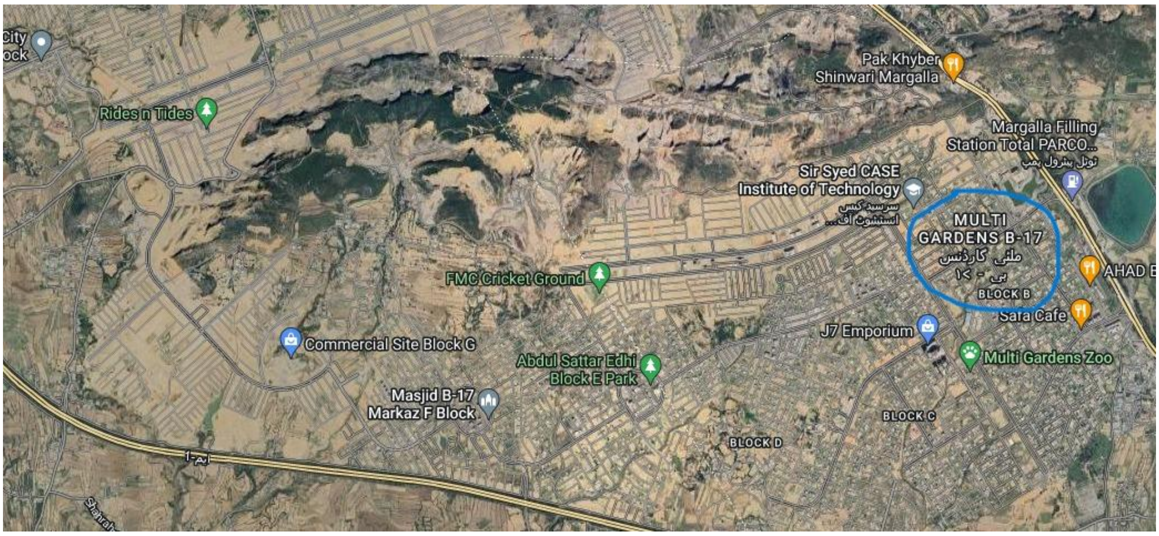

*Figure **Error! No text of specified style in document.**-3 Location of sample collection of Soil (B17 in Islamabad.)*

Material Procurement: The process of material procurement is to acquire the necessary components to complete the study. Specifically, samples from a site were collected, extensively classified by the Unified Soil Classification System (USCS) which classifies soil based on texture and behavior and then analyzed to determine the necessary strength and liquefaction percentages calculated for the geotechnical analysis. To understand the characteristics of the soil along with how they could interact with other components, it was important to understand the soil in this categorization. In addition, sisal fiber in various amounts (5 to 15%) was added to determine the effect of fiber on soil mechanical and physical properties. Soil reinforcement using sisal fiber required critical fiber ratios in determining the efficiency of the sisal fiber itself.

Material testing was separated into two independent phases: one concentrating on the baseline qualities of the soil without any reinforcement, and the other investigating the impact of introducing sisal fiber into the soil.

Soil Testing (without Sisal Fiber): First, several conventional tests of the soil's basic properties were performed during the first step. The specific gravity test was among the tests involved in this; it establishes the relative density of the soil particles and will tell you the composition of the soil. The soil's natural water content was measured by moisture content test; here moisture content test was used as the soil’s natural water content does not have any effect on the soil’s behavior. To examine the soil’s consistency, ATTEST of Limit tests were performed to determine the Liquor Limit and plastic Limit to ascertain the soil’s ability to hold moisture and its behavior on wetting. Standard proctor tests were performed to define soil compaction properties, namely, the optimal moisture content and the maximum dry density that govern how the soil would behave under loading. The strength of soil not laterally confined was assessed by the unconfined compression test. Sieve analysis was finally carried out to determine the sample particle size distribution, which provides information regarding the texture and structure of the sample.

Testing with Sisal Fiber: The soil fiber mixes were evaluated further in the second phase. To determine how the soil’s physical and mechanical qualities are affected by the application of sisal fiber at different percentages (5%, 7.5%, 10%, 12.5%, and 15%) added sisal fiber was applied to the soil. From each fiber–soil combination, the optimum moisture content (OMC) was determined to better understand the moisture needed for best compaction outcomes. The maximum dry density (MDD) of the soil compacts with additional fiber was then measured. The results using the soil alone were compared to those of the soil-fiber combinations in proctor tests. Strength enhancement induced by the inclusion of fiber was determined through the unconfined compression test. In addition, it performed an unconfined test to see how the shear strength of the soil-fiber mixes behave under the shear pressure and was able to get useful data on the effect of sisal fiber on the soil's ability to resist shear pressure.

Varying Percentages of Sisal Fiber: Part of sisal fiber was gradually added to the soil at rates from 5 % to 15 %. This method made it possible to evaluate, in detail, the effect of a wide range of fiber concentrations on the soil's physical and mechanical properties. Then, the results from these different fiber percentages were compared to see what the optimum amount of sisal fiber for soil improvement would be. This comparison study was used to determine what percentage of fiber would increase the soil performance the most, accelerating the soil behaviors of increasing strength, compaction, and overall soil behavior. It was also very important to get a feel for how sisal fiber could be used as a soil-reinforcing material to make the soil suitable for building or agriculture.

4. Analysis and Results

The table shows major differences between soils with and without sisal fiber addition for major soil qualities and shows that sisal fiber addition did not result in any of the evaluated parameters to show any additional differences. The average content of moisture, liquid limit, plastic limit, and plastic index was 25.31%, 27.19, 25.31, and 1.88, all steady. The isotonic swelling results indicate that sisal fiber does not modify the water retention capacity or plasticity of the soil. The uniformity of these qualities indicates that the presence of fiber has a small effect on soil's basic water interaction and plasticity behavior.

The Standard Proctor Test and Modified Proctor Test, which assess soil compaction, showed no change following the addition of sisal fiber. Under the Standard Proctor Test, the maximum dry density and optimal moisture content were 114 lb/ft³ and 13%, respectively, whereas the Modified Proctor Test yielded 123.5 lb/ft³ and 12%. This implies that sisal fiber does not affect the soil's compatibility under standard or modified compaction energy levels.

Table **Error! No text of specified style in document.**.1 Soil Properties Before and After Sisal Fiber

Soil Properties	Before Adding Sisal fiber	After Adding Sisal fiber
Average Moisture Content	25.31%	25.31%
Liquid limit	27.19	27.19
Plastic Limit	25.31	25.31
Plastic Index	1.88	1.88
Standard Proctor Test		
Maximum Dry Density	114 lb/cft	114 lb/cft
Optimum Moisture Content	13%	13%
Modified Proctor Test		
Maximum Dry Density	123.5 lb/cft	123.5 lb/cft
Optimum Moisture Content	12%	12%

The lack of apparent changes in these parameters indicates that the principal role of sisal fiber in soil stabilization is to improve mechanical properties, such as shear strength, cracking resistance, and stability, rather than to affect compaction or plasticity behavior. This agrees with the previous plots, in which shear strength increased with the addition of sisal fiber, while density increased slightly. It appears the use of sisal fiber for strength enhancement while leaving most soil properties unchanged. It is a viable alternative for fields that demand a rise in load resistance without surrendering the additional attributes of the soil, including compaction and details.

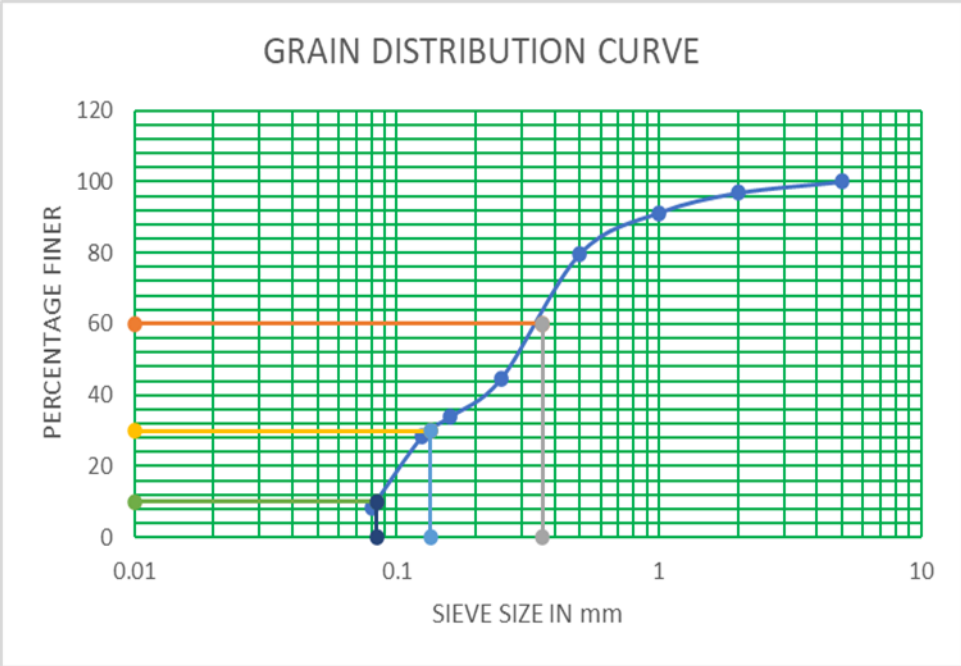

Figure ***Error! No text of specified style in document.****-4 Soil Sample gradation Curve*

According to the above gradation curve as shown in figure 4-1, by using USCS (Unified Soil Classification System), the soil sample is well graded.

4.1 Shear Strength vs Sisal Fiber

The study investigates the shear strength of sisal fiber-reinforced soil, but it does not include direct shear or triaxial tests for precise measurement. Instead, it employs an alternative estimation method that relies on compaction characteristics, deformation behavior, and improvements in cohesion. While this approach provides indirect insights, it lacks the accuracy found in standard shear tests. This limitation affects the precision of the findings. Additionally, the research does not deeply explore factors like fiber distribution and long-term performance in varying environmental conditions, which could influence the effectiveness of the reinforcement.

Three cases with varying sisal fiber % shown on the figure 4-2, are related to shear strength (kPa). The shear strength first decreases and then increases as a percentage of the sisal fiber range increases to ~4-5%, perhaps indicating that the material would degrade during this phase. The shear strength beyond this point increases with the sisal fiber content for all three scenarios suggesting that higher percentages of sisal fiber increase the material's anisotropy in shearing. This trend indicates that the sisal fiber can improve the material performance in some situations with variances in the unique case factors.

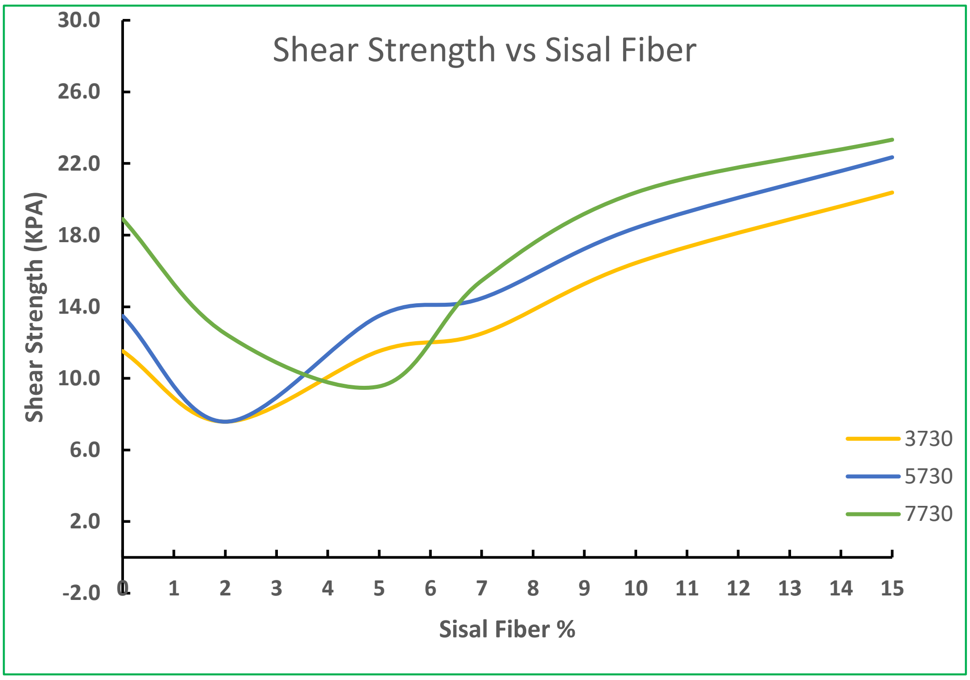

*Figure **Error! No text of specified style in document.**-5 Shear Strength vs Sisal Fiber*

4.2 Optimum Moisture Content vs Sisal Fiber

The Figure 4-3 represents the relationship between Optimum Moisture Content, OMC, to the percent of Sisal Fiber in the material. On the x-axis, the sisal fiber percentage is shown, and on the y-axis the OMC %. At first, OMC increases steeply with increasing sisal fiber content, about 4–5%. Such a result suggests that sisal fiber aids the material’s water-holding capacity, potentially due to its fibrous structure. The OMC then stabilizes at concentrations above this amount, reaching a peak value of about 8-10% sisal fiber concentration. However, increasing sisal fiber concentration above 10% results in a modest drop in OMC, suggesting that excessive fiber content may diminish the material's capacity to hold moisture efficiently. This pattern implies that there is an ideal range of sisal fiber content (about 8-10%) for optimizing moisture retention, which may be crucial for applications that need precise moisture management.

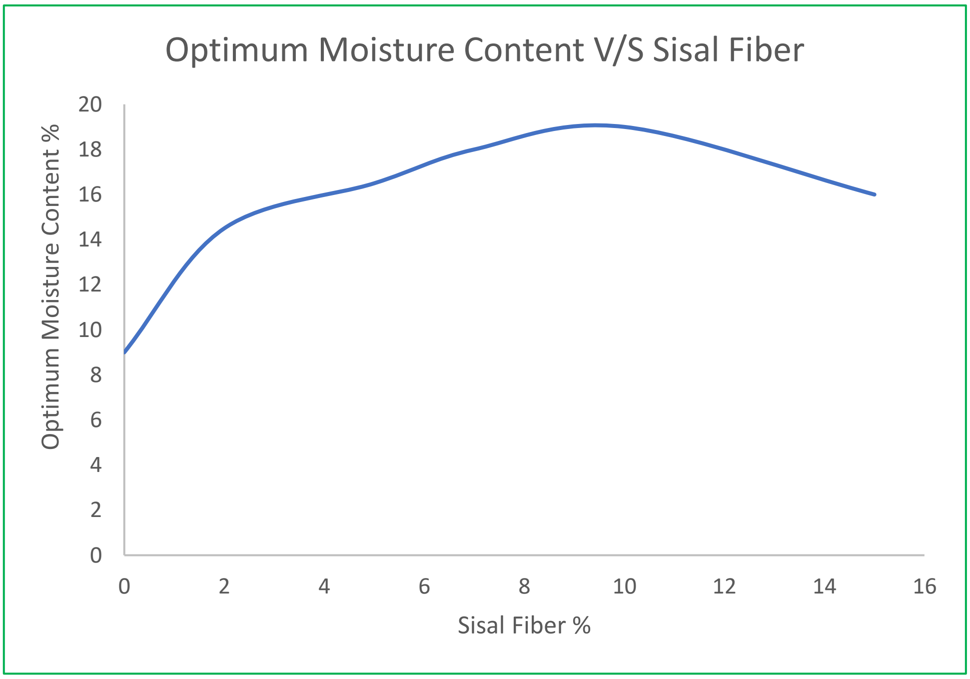

*Figure **Error! No text of specified style in document.**-6 Optimum Moisture Content vs Sisal Fiber*

4.3 Maximum Dry Density vs Sisal Fiber

The Figure 4-4 is presented to show the relationship between maximum dry density (MDD) and sisal fiber percentage. The fraction of sisal fibre is plotted on the x axis and MDD in lb/ft³ on the y axis. This graph shows that the MDD is reduced as sisal fiber is proportion increased. At first, however, the MDD is at its max; with 0% fiber, the material is at its most compact, and further addition of fiber provides no benefit. But above approximately 6–8%, the MDD drops steadily and then stabilizes as the sisal fiber percentage increases. The consequence of this decrease suggests that the addition of sisal fiber leads to void formation or decreases compatibility, probably due to the fibrous structure breaking up particulate packing. This trend suggests there is merit to adding sisal fiber, though at the expense of lower dry density, which may compromise strength and load bearing capability in some applications.

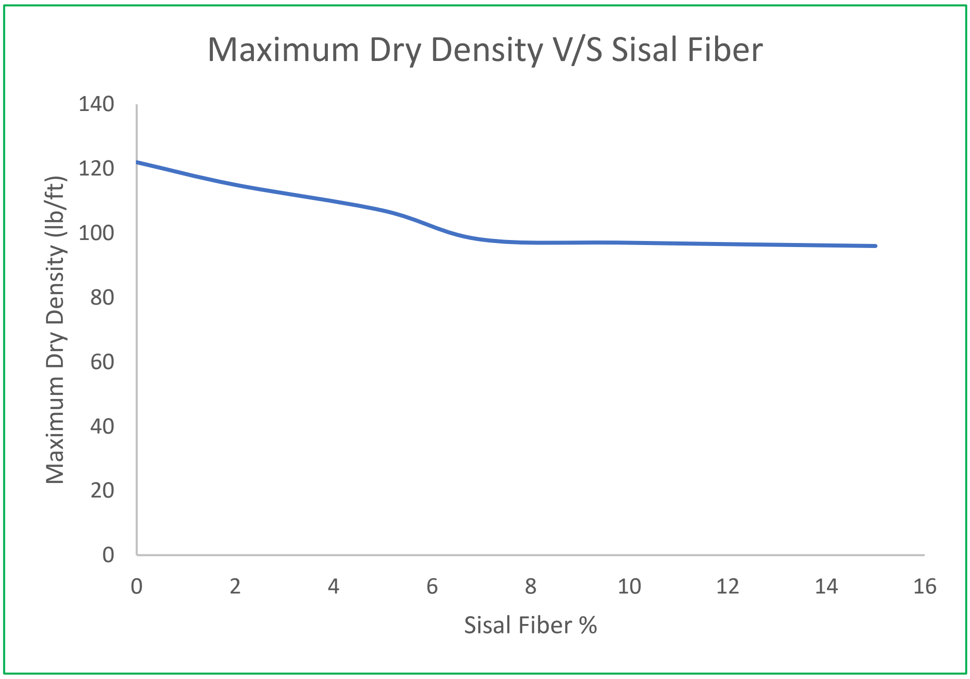

Figure ***Error! No text of specified style in document.****-7 Maximum Dry Density vs Sisal Fiber*

4.4 Deformation vs Shear Load

The Figures 4-4, 4-5, 4-6, 4-7, 4-8, 4-9, and 4-10 exhibit the soil deformation behavior affected in terms of various shear loads and normal stresses, when sisal fiber is added (0%, 2%, 5%, 7%, 10%, 15%, 20 When 0% sisal fiber soil, the shear strength, deformation and stability are poor since larger deformations occur with smaller shear stresses. As figured in the curves, the deformability of the soil is greatly increased using the sisal fiber, in the sense that curves with a gradual increase in deformation with shear stress exhibit improved cohesion and strength resulting from fiber reinforcement. Because the fibers are so effective in dispersing stresses, the best performance of the soil occurs at 5% sisal fiber under the same shear pressures, where the resistance to deformation is the maximum. In this development, increasing the sisal fiber content is found to strengthen the soil, with 5% fiber content the best resistance to shear induced deformation and thus the most effective reinforcement among the tested percentages. Soil shear strength and resistance to deformation are improved by increasing the sisal fiber concentration up to 7%. These extra fibers keep working to give strength to the soil matrix updating its ability to withstand larger shear stresses. However, as compared to the considerable gains found between 0% and 5%, the rate of progress slows. This shows that 7% fiber content may be approaching an ideal concentration, with higher fiber additions providing decreasing rewards in terms of performance improvement. At 10% sisal fiber, the soil has high shear strength and deformation resistance. The fibers efficiently link soil particles, boosting their capacity to withstand greater pressures. Despite these advantages, the efficiency of incorporating additional fibers begins to decline. At this level, clumping or uneven fiber distribution may occur which leads to a lower value of soil reinforcement uniformity. The performance gains less dramatic than at lower concentrations, but 10% fiber concentration remains advantageous. As soil level approaches 15 percent fiber, performance stabilizes with little or no improvement from lower fiber levels. The abundant fibers at this spacing level may lead to poor stress distribution or places of weakness in the soil structure. Cohesion can be impaired by poor fiber-soil interaction, which reduces the potential benefit of additional reinforcement. Excessive fiber content may cause soil loss of structural integrity in some cases. Spectra of up to 20% showed less overall performance compared to lower fiber percentages. Fiber content that is too high will cause clumping, reduce the soil's compaction and create voids that will eventually weaken the soil's structure. While the fibers still aid in reinforcement, the drawbacks associated with overweening reinforcement are starting to counteract the positives. This implies that above 20% amounts of fiber are too high to be efficient in soil reinforcement. At high sisal fiber percentages, the soil's shear strength and resistance to deformation increase vastly until around 5-10%. After this level however, the rate of improvement diminishes and beyond 15-20% of fibre content, effectiveness is reduced. If over reinforced, fiber inclusion may disrupt the soil's structure, which can later lead to imbalances that negate the beneficial effect. As a result of this, an optimal fiber percentage is crucial to obtain the best performance.

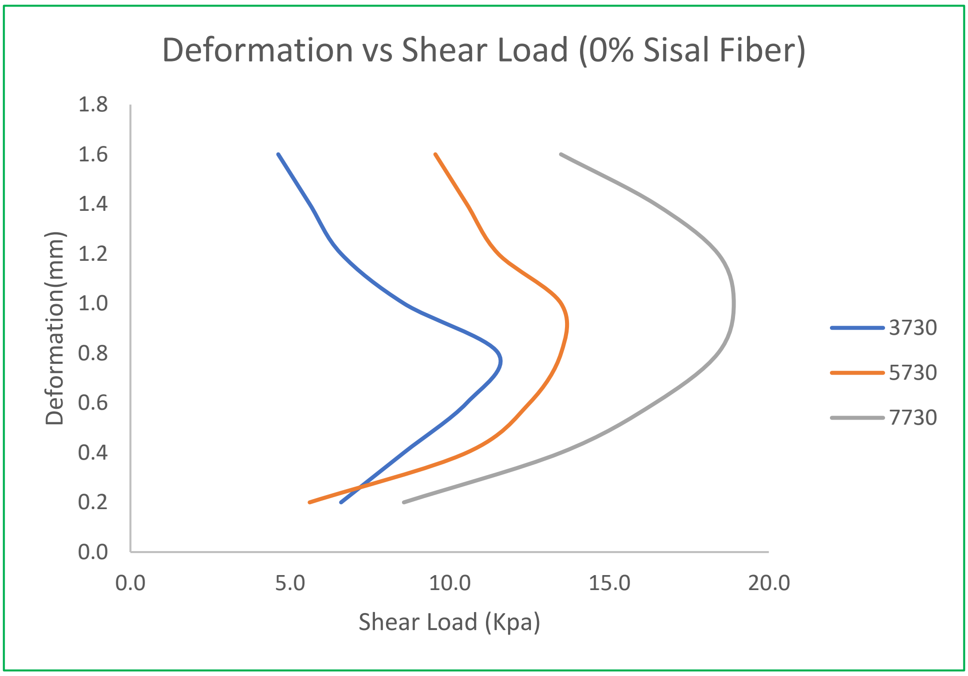

Figure ***Error! No text of specified style in document.****-8 Deformation vs Shear Load (0% of Sisal Fiber)*

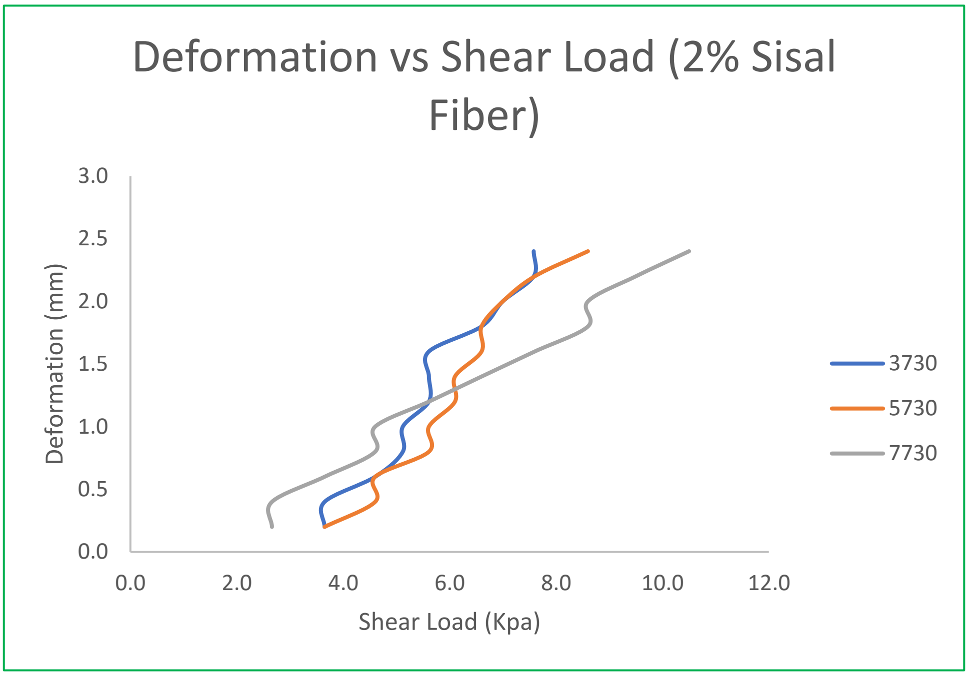

*Figure **Error! No text of specified style in document.**-9 Deformation vs Shear Load (2% of Sisal Fiber)*

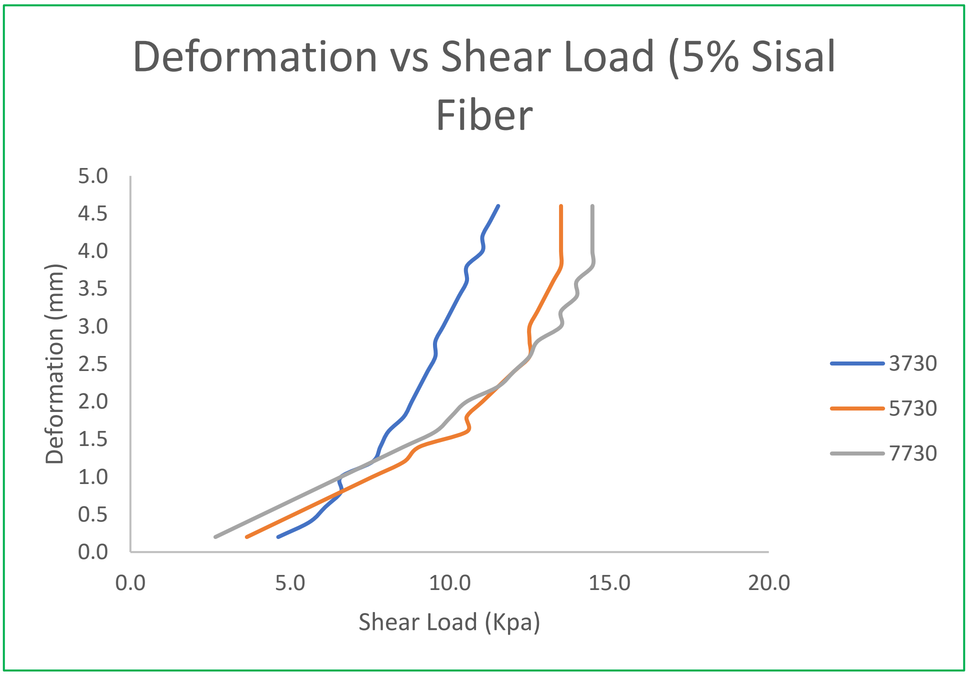

*Figure **Error! No text of specified style in document.**-10 Deformation vs Shear Load (5% of Sisal Fiber)*

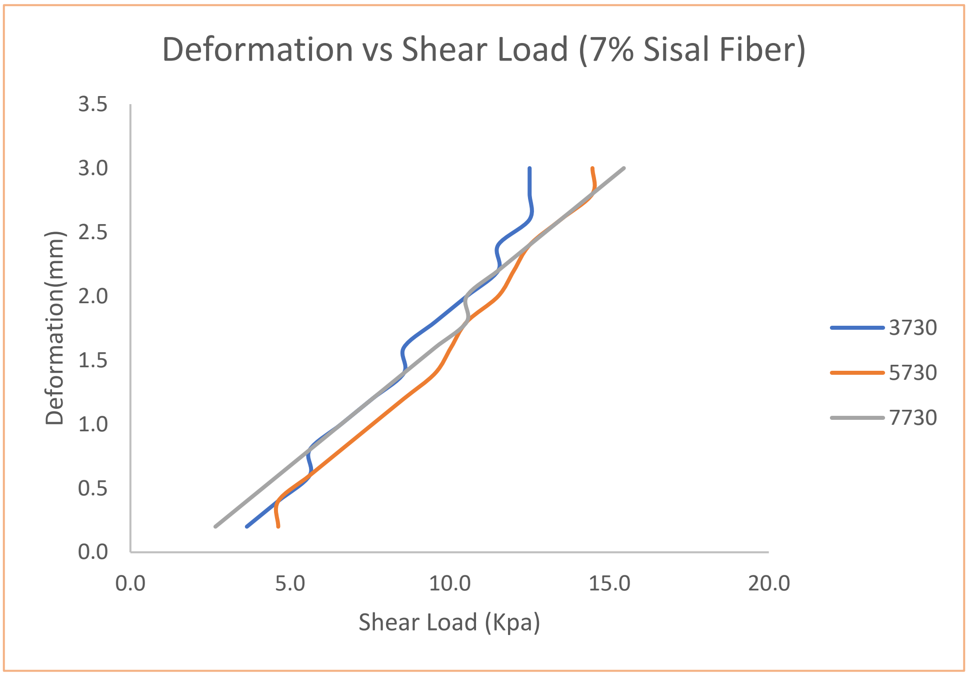

*Figure **Error! No text of specified style in document.**-11 Deformation vs Shear Load (7% of Sisal Fiber)*

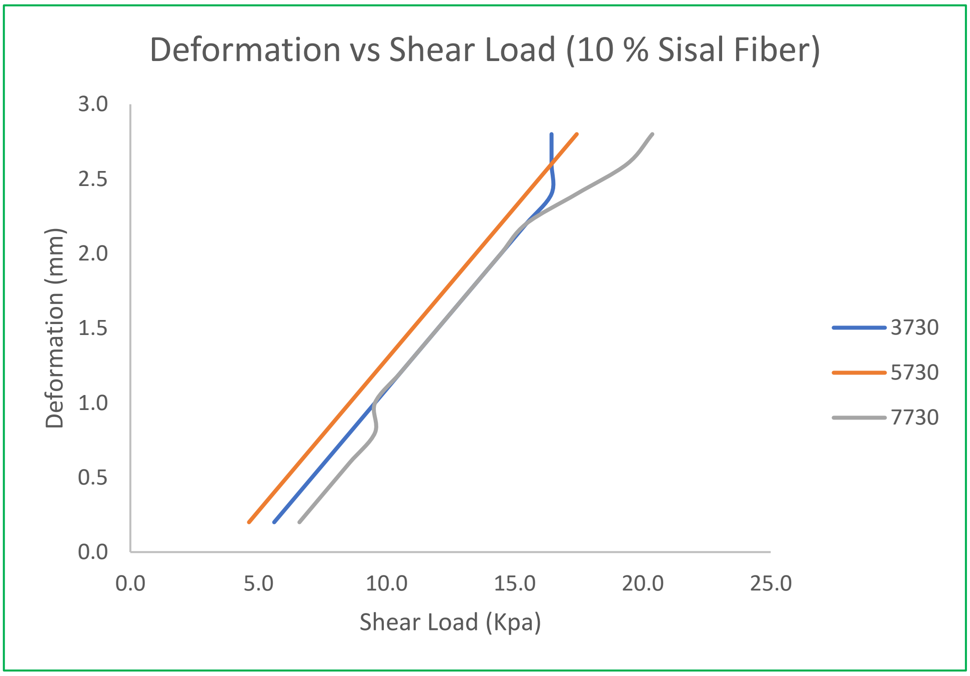

*Figure **Error! No text of specified style in document.**-12 Deformation vs Shear Load (10% of Sisal Load)*

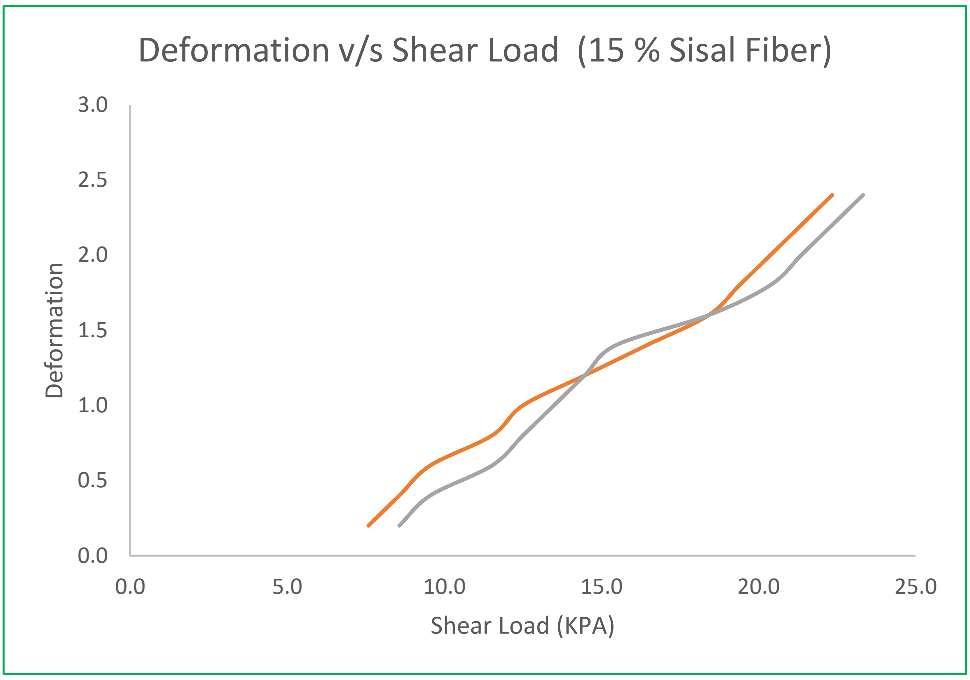

Figure ***Error! No text of specified style in document.****-13 Deformation vs Shear Load (15% of Sisal Load)*

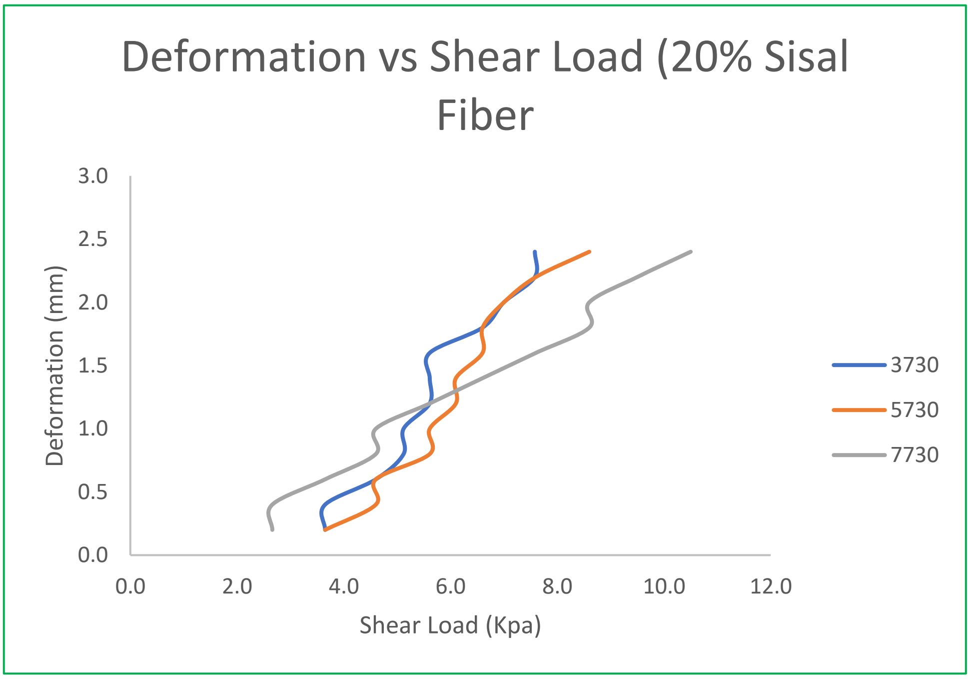

Figure ***Error! No text of specified style in document.****-14 Deformation vs Shear Load (20% of Sisal Load)*

5. Conclusions

The following conclusions are drawn from the comprehensive experimental program discussed.

- When soil is reinforced with sisal fiber, its dry density decreases due to the low specific gravity and unit weight of the fiber. The maximum dry density of the reinforced soil ranges from 1.775 to 1.698 g/cm³. An increase in fiber length (up to 3 mm) and fiber content also contributes to this reduction in dry density.
- The relationship is linear for both parameters. Initially introducing the fiber into the soil leads to an increase in the optimum moisture content (OMC); however, further increases in both the length and content of the fiber subsequently reduce the OMC. The OMC of the reinforced soil ranges from 19.2% to 16.0%.
- The shear stress of fiber-reinforced soil is enhanced by the addition of sisal fiber. The shear stress increases non-linearly with fiber length up to 20 mm, but beyond this length, the shear stress begins to decrease. This reduction occurs because the longer fiber fails to effectively interlock with the soil particles, preventing the soil and fiber from acting as a single cohesive matrix. Additionally, the shear stress of the reinforced soil increases with higher confining pressure (σ3).
- The proportion of fiber content also impacts shear strength, with shear stress improving non-linearly as fiber content increases. However, beyond a fiber content of 0.75%, the shear stress diminishes with further increases in fiber content, likely due to a decrease in the density of the soil-fiber mass.
- The inclusion of sisal fiber increases the value of cohesion in the soil. The maximum cohesion value achieved is 66 kPa, compared to only 18 kPa for unreinforced soil. Up to a fiber length of 20 mm, the cohesion value continues to rise with increased fiber length.

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