Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 2, 496-515
2025
Publisher: Learning Gate
DOI: 10.55214/25768484.v9i2.4516

Performance of fiber-reinforced clay soil

Sumesh Narayan[1]*, Avneel Prasad[2], Sahil Shanil Goundar[2], Farid Mahboubi Nasrekani[1]
[1]Discipline of Mechanical Engineering, School of Information Technology, Engineering, Mathematics and Physics, The University of the South Pacific, Fiji; sumesh.narayan@usp.ac.fj (S.N.) farid.mn83@gmail.com (F. M. N.)
[2]Discipline of Civil Engineering, School of Information Technology, Engineering, Mathematics and Physics, The University of the South Pacific, Fiji; S11185532@student.usp.ac.fj (A.P.) S11185485@student.usp.ac.fj (S.S.G.)

Abstract: The perfect type of soil for construction purposes is rare to find. Thus, there is a need to stabilize these soils based on their requirements. When it comes to clayey soil, the situation is even more difficult compared to most other soils. Clayey soil is classified as expansive soil, which means it expands when it absorbs a lot of water and shrinks when it dries up. Clay soils also don't have much shear strength and bearing capacity to hold up a structure without any treatment. Waste fibers are the best solution to this, especially here in the Pacific, where we have an abundant supply of coconut waste whose husks are fibrous and suitable for reinforcing soils upon treatment. This is not only an environmentally friendly way to stabilize clayey soil but also a cost-effective method. This study focused on reinforcing clayey soils with fibrous materials such as coconut husk (coir), bamboo fiber, jute, and nylon ropes, which are available locally. These fibers were both mixed as short fibers in the soil matrix and woven into geogrids using the fibers to improve strength. Soil was also aided with stabilization using cement and lime to see the difference between treated and untreated fiber-reinforced soil samples. It was found that the addition of bamboo short fibers at a 1% ratio was the most effective solution. It can be observed that the addition of 1% fibers does result in about a 35% improvement in bearing strength over unreinforced soil, with a maximum of 12.31 CBR achieved. Through the addition of 5% lime and 5% cement to fiber-reinforced samples, a maximum compressive strength of 2.46 MPa was achieved.

Keywords: *Clayey soil, Compressive strength, Construction materials, Fiber-reinforced, Sustainability.*

1. No Table of Figures Entries Found Introduction

Civil engineers and contractors around the world encounter a lot of problematic soil while building any infrastructure. Expansive soils such as clay are no exception. Clay soil has a high tendency to not only expand with increase in moisture content due to its high plastic limit but also shrink as it dries up. Thus, there is a need for ground improvement techniques on these types of soils. Soil stabilization using fibres is one of the most effective ways to improve the engineering properties of problematic soils. This method significantly improves the shear strength and ductility of the soil. Unlike chemical stabilization methods such as lime and cement, the performance of fibre reinforced soil is not adversely affected by weather conditions. Thus, this study focuses on reinforcing clayey soils with different material fibres.

Many authors Freilich, et al. [1]; Tong, et al. [2]; Chaple and Dhatrak [3]; Amena and Chakeri [4] and Lakshmi, et al. [5] have previously investigated the performance of fibre reinforced soils and concluded that fibres enhance the response of the soil as it mobilizes the tensile strength of the shear planes in the soil. This improves shear strength and ductility of the soil. Most soils have adequate strength and reasonable shear strength but have very poor tensile strength. In the case of expansive soils, such as clay soil, it is relatively weak in all three strength categories and hence it is not good for engineering use. Fibres have excellent tensile strength, friction, and adhesive properties. Most of the

History: Received: 30 September 2024; Revised: 20 January 2025; Accepted: 21 January 2025; Published: 31 January 2025
* Correspondence: sumesh.narayan@usp.ac.fj

previous studies Tong, et al. [2]; Yang, et al. [6]; Shen, et al. [7] and Akbulut, et al. [8] of fibre reinforced soils have been based mainly on tensile strength. Moreover, just a handful of studies Freilich, et al. [1]; Yang, et al. [6]; Hejazi, et al. [9]; Huang, et al. [10] and Gong, et al. [11] have been conducted on clay soil reinforced with fibres and these studies have not yet recognized the necessary mechanisms involving the performance of fibre reinforced clayey soil nor have they established the conditions that might affect the performance of this mixture. Most of these studies, however, indicated there is room for more research on this topic and mostly used distributed arrangement of fibres for the soil reinforcement. This leaves a lot of void spaces at every cluster where the soil and the fibres are bonded together. This results in the soil holding more water in these void spaces which would significantly affect the engineering properties of the soil, especially the shear strength of the soil and the rate of settlement that could increase due to more water being expulsed from the void spaces leading to greater loss of volume more rapidly. Fibre reinforced soil is the future of soil stabilization especially if it involves waste fibres such as coir, plastics, jute etc. In this fast-growing world with many synthetic designs coming up, innovation needs to be applied to find effective techniques that would not only solve the environmental problems but also be cost effective and easy to implement.

2. Literature Review

Soil reinforcement using fibres has been a natural phenomenon and has been recognized by humans in ancient times and has been implemented in various methods ever since. Through the ages, researchers have experimented with different fibre arrangements and have found improvements in strength in both short fibres and fibre geonets. The treatment of natural materials, its influence on the strength of clayey soil, and environmental effects of these treatments are discussed further in this literature review.

2.1. Need For Reinforcing Soils

The integrity of an entire structure depends on the engineering properties of the soil it is built on. The ideal type of soil for both building and road construction is loam soil due to its ideal combination of silt, clay, and sand. It does not expand, nor do shrink or shift and can handle significant volumes of water well by allowing proper drainage. However, not all construction sites are blessed with this type of soil. Many sites include problematic soils such as clayey soils that need to be stabilized. Clay is not the best soil type for construction purposes due to its tendency to expand and shrink as it moistens and dries up. This means that settlements can occur rapidly leading to cracks and fissures in the infrastructure. Thus, it is important to reinforce soils, especially clayey soils to increase its stability and enhance its engineering properties. Soil reinforcement is one of the many ground improvement techniques for soil stabilization used since ancient times such as dewatering, densification and use of admixtures. However, what makes it different from other ground improvement techniques is that it can last longer and not lose its engineering properties due to changes in weather conditions. Reinforced soil is a composite mass where elements that resist tension such as geosynthetics and fibres are embedded in the soil to increase its stiffness, strength, permeability, and compressibility. This can be used in various construction practices including embankment, pavement, retaining walls, foundations, and slopes. Clayey soils generally have low shear strength and poor load-bearing capacity. Reinforcing these soils can enhance their strength and stiffness, allowing them to withstand higher loads and prevent excessive settlement or deformation. This is particularly important when constructing foundations, embankments, or structures on clayey soil.

Furthermore, clayey soils are prone to slope instability, especially when subjected to water infiltration or changes in moisture content. Reinforcing the soil with appropriate materials, such as geosynthetics or geogrids, can increase the soil's stability by providing tensile strength and reducing lateral movements. They can also erode easily due to the cohesive nature of the particles and their susceptibility to water erosion. Reinforcement measures like erosion control blankets, or geosynthetics can help protect the soil from erosion by stabilizing the surface and improving surface water runoff. In areas with non-uniform soil conditions, differential settlement can occur, leading to structural problems in buildings or infrastructure. Reinforcing clayey soils can help distribute loads more evenly and minimize differential settlement, ensuring the stability and longevity of structures. Clayey soils also have poor resistance to seismic forces due to their low shear strength and high compressibility. By reinforcing the soil with techniques such as soil nails, ground anchors, or soil improvement methods like soil mixing or deep soil mixing, the overall seismic performance of the soil can be improved.

2.2. Overview of Fibre Reinforcement

Hejazi, et al. [9] in their review paper, mostly focused on analyzing the strength improvement provided by fibres (natural and synthetic) and did not consider any soil treatment. The natural fibres reviewed in their research were coir, sisal, palm, jute, flax, barley straw, bamboo, and cane whereas polypropylene, polyester, polyethylene, glass, nylon, steel, and polyvinyl were analyzed for the synthetic fibres. Due to landfills being filled up all over the world, non-renewable sources of fibre reinforcement are becoming increasingly costly, hence they suggested to use natural fibres, which for the most part are regarded as waste materials. The usage of some synthetic fibres, such as polypropylene and polyethylene are also very good options, but there comes the question of production and sustainability of these fibres, and this is where natural fibres get the edge [9]. Further, when preparing samples, there is no standard to conform to and the major problem with short fibres is that they get tangled, which makes it difficult to obtain a homogeneous mixture. If the mixing of fibre and soil cannot be effectively done at a small scale, it will not be feasible to develop large scale production of fibre reinforced soil mixtures. They also outlined some important possibilities where soil reinforcement using fibres can be feasible if executed correctly, such as subgrades of pavement layers, retaining walls and embankments, protection of slopes and foundations, and even possibly earthquake resistance. They have stated that for every type of fibre there will be an optimum content and length and have concluded that for the most part, the fibre content should be equal to or less than 1% and the fibre lengths should be between 12-35 mm.

2.3. CBR Test Summary

Many researchers Chaple and Dhatrak [3]; El Majid, et al. [12] and Tamassoki, et al. [13] have used the CBR test as the core of their assessment of clayey soils. During their analysis, Chaple and Dhatrak [3] used coir as the main reinforcement medium. Fibres were used at 0.25%, 0.5%, 0.75%, and 1% contents, however, the lengths of the fibres were kept constant. The major strength test conducted was the model footing tests, in which they compressed the reinforced soil in a mold to simulate a real-world footing of a building. They focused their efforts on improving the bearing capacity and settlement resistance of the soil. They observed that the optimum fibre content was 0.5% to achieve a settlement of 3 mm under 1600 kN/m^2 of stress. The unreinforced sample had a settlement of 4 mm with 800 kN/m^2 of stress, which means that fibre reinforcement was able to improve the settlement resistance by two times. The depth of the reinforcement also played a part, as it was noted that a depth of quarter of the footing is ideal. The ultimate bearing capacity was also greatest at this depth and fibre content, which was 665 kN/m^2, compared to 570, 590, and 525 kN/m^2 for the 0.25%, 0.75% and 1% samples at the same depth. Generally, the results show that the inclusion of fibres improves the bearing capacity and reduces the settlement of clay soil, providing an economical and sustainable reinforcement method. El Majid, et al. [12] in their study used three natural fibres which were alfa, jute and sisal fibres in 1%, 3%, 9%, and 18% percentages and 10, 30, and 90 mm lengths to improve the soil's bearing capacity and free swell properties. They found that longer fibres (90 mm) and higher fibre content (18%) was more effective in improving the free swell of the soil whereas the 10 mm and 30 mm fibres at lower contents (1% and 3%) were more effective in improving the bearing capacity of the soil. They concluded that to improve both properties, it is recommended to use fibre lengths between 20-40 mm at 3-9% fibre content. Tamassoki, et al. [13] in their research investigated the effects of adding activated carbon, coir fibre, and lime to their clay soil samples which they described as their ACFL samples. Activated carbon was added in 3% contents, whereas coir and lime were added at 0.5% and 9% content respectively and they also tested samples with only coir and lime reinforcements for comparison. They were able to achieve an impressive CBR of 92.79% with their ACFL sample compared to 10.6%, 11.21% and 20.14% of unreinforced, coir and lime reinforced samples. The ACFL sample had significantly higher CBR which Tamassoki, et al. [13] stated was due to the inclusion of activated carbon.

2.4. Shear Test Summary

Freilich, et al. [1] in their research conducted triaxial shear tests on commercially available polypropylene geo-fibres to determine the shear strength of fibre reinforced clays. Two kinds of triaxial shear tests were conducted, which were isotropic consolidated-undrained (ICU) triaxial and isotropic consolidated-drained (ICD) triaxial testing. The difference between these two tests is that the undrained tests measure the maximum shear strength without removal of pore water pressure, whereas the drained shear tests are conducted on soil after removing pore fluid. Unreinforced samples were also tested to develop failure envelopes to compare with the reinforced samples. Results from the ICU and ICD tests revealed that inclusion of fibres changes the behavior of the clay soil during sharing, and ultimately altering the pore water pressures generated within the specimens. The failure envelopes were much greater for the fibre reinforced samples when compared to unreinforced soil, which means greater shear stress would be needed in the reinforced sample for failure to occur. Moving on, Shen, et al. [7] in their research have looked at how lime and cement affect the strength characteristics of clayey soil which has already been reinforced with fibres. A series of consolidated undrained (CU) triaxial shear tests were conducted to test the shear properties of the soil samples in this investigation. Before treatment of soil, the samples were reinforced with polyester fibres at 0.05%, 0.1%, 0.2% by weight to evaluate what the effect of fibre reinforcement alone has on the soil. It was seen by the results that the undrained shear strength of fibre reinforced soil increased with increase in fibre content with the peak shear strength reaching up to 200 kPa with 0.2% fibre content. Furthermore, lime and cement were added in 5% content to the already reinforced samples, and were cured for 28 days. It was found that the addition of lime or cement greatly increased the shear strength of the fibre reinforced samples, where cement was more effective in improving the strength of the samples. By the addition of 5% lime, the peak shear strength reached up to 600 kPa whereas with the addition of 5% cement, the peak shear strength reached 700 kPa. The cohesion between the particles was also much greater in the cement added samples, this is because cement has greater bonding properties compared to lime.

While most of the articles only focused on the strength improvements provided by fibre reinforcement, Huang, et al. [10] included testing the cracking behavior along with shear strength of reinforced samples. Due to repeated expansion and contraction of clay soil, the soil becomes weak over time, this is especially a problem in clay soil because it is highly expansive. Two types of fibres used by Huang, et al. [10] were glass fibre and polypropylene fibre. The fibres were included in 0.1%, 0.3%, 0.5% and 0.7% contents. The soil matrix with higher fibre content showed smaller crack length and width, with glass fibre providing a slightly better improvement in crack resistance. In contrast, polypropylene fibres were more effective in improving the shear strength of the soil. The maximum cohesion was 95 kPa at 0.3% fibre content, the maximum angle of angle of internal friction was 23° at 0.5% fibre content. Due to this, a maximum shear strength of 250 kPa was achieved at 0.5% fibre content whereas the glass fibre reinforced samples were able to achieve a shear strength of 220 kPa at 0.3% fibre content. Polypropylene has a much rougher surface than glass, which is why the polypropylene reinforced samples exhibited greater shear strength.

2.5. UCS Test Summary

During their research, Lal, et al. [14] have tested the performance of coir geotextile reinforced sand beds by conducting the plate load test on square modelled footings. The footings rested on the sand beds reinforced with the coir geotextile, which were arranged in geocell and planar forms. It is important to note that this test was done on sand, which is less problematic and exhibits greater strength properties when compared to clay. They have also predicted that the degradation of the coir geotextile in the soil may only have a slight effect on the performance of foundations in the long term because the soil will reach its own ultimate strength with time due to the applied vertical pressure. Coir was weaved using a machine and placed in soil in layers having dimensions of 150 mm × 150 mm, which is the same size as the footing plate, and the plate load test tank had a dimension 5 times that of the footing plate size, which was 750 mm. This was done to account for the scale effect, due to which, the reinforced soil may behave differently when implemented in real world applications. It was observed that for an equal quantity of material, the geocell arrangement provided an improved performance compared to the planar arrangement. For a settlement of 25 mm, the maximum bearing stress resisted by the geocell tests was approximately 2.5 MPa whereas for the planar arrangement, the maximum bearing stress resisted was close to 1.8 MPa. It was also concluded that the maximum depth at which these geocells and planars should be placed is at 0.5 times the width of the footing, and any depth greater than this does not provide any strength improvements at all. Moving on, Yang, et al. [6] studied how reinforcing cement stabilized soil with a natural fibre (rice husks) and with synthetic (polypropylene) fibres affect the compressive and split tensile strength of the sample and places where this type of reinforcements is applicable. They conducted tests on cement stabilized soil, sandy clay of low liquid limit, and low liquid limit clay soil which were all reinforced with the two fibres at varying content and curing time (14 days and 28 days). The fibre length of the polypropylene was maintained between 10-15 mm and the rice husks were between 10-12 mm as its length cannot be effectively changed. The fibres were added at 0.3%, 0.5%, and 1% of the dry unit weight whereas cement was added at 10%. The experimental data that Yang, et al. [6] provided shows that the addition of the two fibres significantly improved the results of unconfined compressive strength (UCS) and the split tensile strength (STS) of the samples. The cement-stabilized specimen showed brittle failure in both the UCS and STS tests, which was minimized when fibres were added to the next set of experiments. It was justified that the fibres help with the transfer of force between the cracks, which makes the samples less brittle, and also increasing its compressive and tensile properties. The most strength gains were achieved at a fibre content range of 0.3-0.5%, and it was observed that rice husks provided a better strength gain in the UCS and STS tests whereas the polypropylene fibres only provided significant strength gain in the UCS test. The effect of curing time also had an impact on the results of the UCS and STS tests, where it was seen that the sets which had a curing time of 28 days displayed greater strength improvements. It was concluded that rice husk is overall a better alternative to polypropylene fibres.

Furthermore, Akbulut, et al. [8] in their study aimed to modify clay soils using waste synthetic fibres to improve its unconfined compressive strength. The fibres used in their investigation were scrap tire rubber, polyethylene, and polypropylene from waste materials such as plastic bags. The fibres were implemented randomly in various content, 1 to 5% for scrap tire rubber and 0.1-0.5% for the polyethylene, and polypropylene fibres. The lengths of these fibres were also varied at 5, 10, and 15 mm. The test results confirmed that these fibres improved the compressive strength. It was seen that as the optimum tire rubber content and length to achieve the maximum UCS of 190 kPa was 2% and 10 mm respectively whereas for the polyethylene, and polypropylene fibres it was 0.2% and 15 mm respectively, which reached a UCS of 150 kPa and 170 kPa respectively.

DOI: 10.55214/25768484.v9i2.4516

2.6. The Effects of Treated Vs Untreated Materials on Strength

Chemical stabilization has been utilized for ages to treat weak expansive soils such as clay. Soil is mainly treated with lime, cement, or ashes of natural materials such as bagasse ash, wood ash, and rice straw ash. These can be added in soil at different percentages ranging from 1% up to 15% depending on the requirement [9]. These additives chemically improve the strength of soil, and if the soil is not very weak, this can alone be enough to provide stabilization. As in the case of natural fibres, they are treated to prevent their decomposition. Different fibres undergo different treatment processes. Mainly, sodium hydroxide (NaOH) can be used to treat coir and bamboo fibres. NaOH is a good option because it also improves the tensile strength of bamboo fibres and coir. Treatment of fibres also reduces the transfer of moisture between the soil matrix and the fibres, which ensures that the fibre's strength is not compromised Hejazi, et al. [9]. Amena and Chakeri [4] during their research conducted the free swell test on treated (with lime) clay soil and untreated clay soil, and they found that the untreated soil had a free swell percentage of 103%, which indicates that the soil sample is highly expansive. After adding lime, the free swell percentage of the soil reduced from 103% to 86%, which is a significant improvement. They also observed that with the addition of plastic strips to the already lime treated soil further reduces the free swell percentage. Shen, et al. [7] in their research conducted series of consolidated undrained (CU) triaxial shear tests and unconfined compression (UC) tests and found that with addition of both lime and cement improved the strength of their sample drastically, with a great improvement noticed with cement stabilization.

2.7. Environmental and Economic Effects

Failure of soil embankments, slopes, and maintenance and repair of roads are some of the problems which leads to huge expenditures in countries throughout the world. The increasing costs of artificial geosynthetics and the need for more sustainable solutions has pushed the approach to implement natural soil stabilization methods as an alternate to artificial ones. Limestone and ashes of materials are economical to use as stabilizers as shown in numerous studies Lakshmi, et al. [5]; Das and Sobhan [15] and Vijayan and Parthiban [16]. However, chemical stabilization is not environmentally friendly. Chemical treatment of soil has long term effects on soil. For example, after the chemicals are added to the soil, it changes the pH of the soil, and this causes environmental pollution and can also harm the organisms in the area [11]. Moreover, there can be nutrient imbalances due to the added lime. It can decrease the availability of some nutrients like manganese, iron and zinc and therefore lead to deficiencies in plants [14]. This has urged engineers to implement physical soil stabilization methods like natural fibres. Most of these natural fibres like coir and bamboo fibres are industrial or rural waste which makes it very cost-effective and environmentally friendly. However, the drawback of using natural fibres is that they would eventually decompose in soil if it were used untreated. With the treatment of either soil or fibres, there is the introduction of chemicals into the natural environment. These chemicals can leach into the soil if they break down or react with another element. Therefore, it is necessary to use the correct treatment processes to avoid any harm to the environment.

2.8. Applications

Tables 1 and 2 shows the fibres used in the current study and some possible applications, respectively. Fibre reinforcement in clayey soils can have several applications across various engineering fields. Table 2 shows some common applications of fibre-reinforced clayey soils:

Table 1.
Fibres employed and reasons for its use.

Fibres	Reasons
Bamboo	• Bamboo fibres exhibit high tensile strength which means that they can resist pulling forces as well as prevent deformation and cracking of the clayey soil. • They are also highly flexible and can withstand movements, settlement, and consolidation in soils. • Bamboo is compatible and forms strong bonds with the clay particles which improves the cohesion of the soil ultimately increasing its shear strength. • Bamboo reduces the moisture variation of clayey soil which helps in controlling its expansive nature. This means that there is less consolidation and settlement of the soil. • Bamboo is also readily available in the South Pacific and is a cost-effective solution to reinforce clayey soil.
Coir	• Coconut is one of the most readily available natural materials in the pacific. One can cut the trunks to build a structure, use the bark for tapa design, use the leaves for weaving artifacts and clothes, use the sasa sticks for broom, husks for scrubs, drink the coconut water, eat the flesh, use the coconut milk and even use the remaining shell for bowls. Further, another important resource which could be useful as the world is in desperate need of creating sustainable designs, reinforcing soil is not an exception. • It is resistant to moisture; hence the moisture content of the soil will not affect the fibre. • Coconut husk fibres exhibit high tensile strength which means that they can resist pulling forces as well as prevent deformation and cracking of the clayey soil.
Nylon	• Nylon was chosen primarily due to its evident high strength properties.
Jute	• Jute was chosen due to its cost effectiveness and high strength to weight ratio. It has great tensile strength and do not affect the environment.

Table 2.
Possible applications of fibre reinforced soil.

Application	Performance	Required values
Road construction	Enhanced foundation for the road to be constructed on. Increased bearing capacity, shear and compressive strength of the soil as well as reduced deformations. Overall, a much stable base for transportation is provided	CBR: • Low Volume Roads: 5% - 10% • Moderate Volume Roads: 10% - 15% • High Volume Roads: 15% - 20%. Shear strength: • Low Volume Roads: 75-100 kPa • Moderate Volume Roads: 100 – 150 kPa • High Volume Roads: 100 – 200 kPa Compressive strength: • Low Volume Roads: 0.2 – 0.3 kPa • Moderate Volume Roads: 0.4 – 1 MPa • High Volume Roads: 1 – 3 MPa
Embankment and slope stability	Enhances the stability of the embankments as the fibres increase the tensile strength of the soil and improves its resistance to deformations. It also improves the overall stability of the ground as it can carry more loads without deformations. The chances of slope failures are also low due to enhanced stability.	CBR: 5% - 20% depending on the embankment's slope, where greater slopes require higher CBR Shear strength: 75 – 150 kPa Compressive strength: 0.5 – 3 MPa depending on the embankment's slope, where greater slopes require higher compressive strength.
Seawalls/Retaining walls and coastal protection	Geonets can be utilized to reinforce as well as protect the coasts from eroding as it significantly reduces the momentum of the waves as well as prevent sedimentation due to presence of finely weaved geonets.	CBR: 5% - 20% depending on the height of the wall, where greater height requires higher CBR Shear strength: 100 – 150 kPa Compressive strength: 0.5 – 2.5 MPa depending on the height of the wall, where greater height requires higher compressive strength.
Soft ground improvements for foundations	Soft grounds can also be improved by reinforcing them with fibres. These fibres would help distribute loads and increase the shear strength of soft soils which would reduce its tendency to settle under loads and improving its overall stability.	CBR: 5% - 10% depending on the weight of the house. Shear strength: 100 – 200 kPa depending on the weight of the house. Compressive strength: 0.5 – 2 MPa depending on the weight of the house.

3. Materials and Methods

3.1. Soil Preparation

The soil was taken out from the bags and was then placed in the oven for drying overnight. The oven dried soil was then hammered into finer particles to make the most use of the soil and then the soil sample was allowed to cool and later sieved through multiple sieves depending on the test performed. This entire process was followed before conducting each test carried out in this research work.

3.2. Tests Performed on Unreinforced Soil

Proctor test - the sole reason to perform this test was to determine the optimum moisture content (OMC) and maximum dry unit weight of the soil sample. Soil samples of five different moisture content is transferred to the proctor compaction mold, and then compacted in three different layers using a 2.5 kg rammer which is dropped from a constant height of 305 mm. After each test the sample was scraped off into a moisture can. The moisture can was then placed in the oven overnight for drying. The dry density and the OMC were theoretically calculated.

Liquid limit test - an oven dried sample was sieved through 450 microns sieve to obtain very fine particles. Water was then added to the sample and mixed until it was uniformly distributed throughout the soil. Then the Casagrande's apparatus was set up and it was ensured that there was no moisture present in the apparatus. The cup was then filled with the moist soil and smoothened with the spatula. The grooving tool was then used to create a groove by sliding it along the cups center in the vertical direction. The cup was then dropped from a height of 10 mm at a constant rate until the soil sample was split into two by the groove. The number of blows required was recorded and the procedure was followed for multiple trials.

Plastic limit test - this was done by adding water to the soil sample until it was pasty enough but did not stick to the hands and rolled into 5 mm threads. This sample was then placed in the moisture can, to determine the moisture content upon oven drying. The plastic limit was then determined.

Swell test - a clayey soil sample of 100 cm^3 was placed in a measuring cylinder and water was added. The change in volume after a day was then recorded.

CBR penetration test - this was one of the main test conducted in this study which was done to find the bearing capacity of the soil samples. This test was conducted for both unreinforced and reinforced clayey soil. The soil samples were sieved through 150 microns sieve and mixed with 26% water content of the total mass of the soil as this was the optimum moisture content at which the soil would exhibit its maximum strength. After the soil was mixed with water uniformly, the CBR mold was prepared by compacting it in three equal layers with 56 blows in each layer. The base plate and extension were then removed, and the sample was placed in the CBR equipment for testing. Here, a 50 mm diameter steel plunger penetrates the soil sample at a controlled rate. The force required to penetrate the sample at different penetration levels gave the CBR percentage values.

Direct shear test - this test was done to determine the ability of soil to resist shearing forces. Firstly, the soil is compacted in the plates and then placed in a direct shear box. The horizontal and vertical dial gauge were then calibrated and the shear box was then horizontally moved across its central axis at a controlled rate to find the shear strength of the soil sample. For this test, it was hypothesized that the geonet would perform better than shorter fibres.

3.3. Test Performed on Fibre-reinforced Soil Sample

3.3.1. Fibre preparation

Bamboo was cut and then kept in a drum containing caustic soda solution for a week and then was sun-dried. The bamboo was then beaten with hammer to soften it further and then thin fibres were extracted. This was then cut into 10 mm and 20 mm pieces for multiple ratios and tests. Coconut fibres were pulled out from the husks. It was noticed that some fibres were thick and highly compressible and also possessed low tensile strength. Thus, the fibres were scrubbed repeatedly until only the fine and strong fibres remained. This was then cut into 10 mm and 20 mm pieces for multiple ratios and tests. Further, nylon and jute fibres were simply obtained by cutting and loosening nylon and jute ropes into 10 mm and 20 mm fibres.

3.3.2. Geogrid Preparation

The best strands of coir and bamboo fibres were selected and then weaved. Eleven geogrids of bamboo and nine of coir. The geogrids were made like a net with 20 mm gaps as shown in Figure 1. The joints were tied using strings so that they do not dislocate during the test.

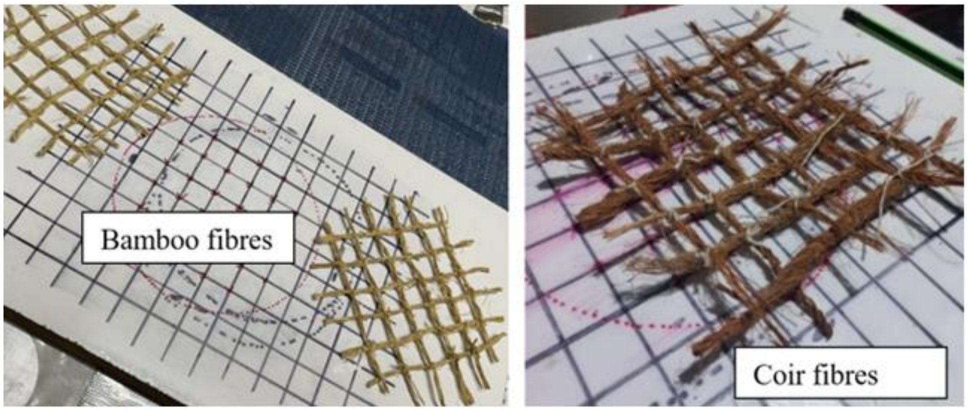

Figure 1.
Geogrid made from bamboo fibres and coir fibres.

The following tests were performed on fibre-reinforced soil; CBR test - the procedure for this test was the same as the unreinforced clayey soil. For the samples with geogrid; geogrids were placed in the middle of the 2nd layer, on the top of the 2nd layer and in the middle of the first layer. The compaction process remained the same.

Direct shear test - three tests were carried out where one was with short fibres, one with geonets and one with combination of both.

Unconfined compressive strength (UCS) test - upon CBR testing it was found that bamboo fibre was the best choice. Soil samples were prepared in three sets where the first set involved mixture of soil with both lime and cement at 2.5%, 5% and 10% respectively. This was done to determine the best percentage of both lime and cement to use for the main UCS tests. Once the optimum ratio was determined after 7 days of curing and testing, the second set of soil samples were prepared. This set included three samples which were soil and lime mixture reinforced with: short fibres, geogrids and combination of both short fibres and geogrids. This was done to determine the best fibre arrangement for the rest of the UCS tests. It was found from the second set of tests that the short fibre arrangement was slightly better than the combination of short fibres and geogrids. Thus, only short fibres were used for the final set of samples. The procedure for each test is as follows.

1. The soil was conditioned with 26% water for each sample prepared after which lime or cement was added as the required ratio and mixed thoroughly. Fibres were then mixed as required for the particular sample.
2. The mold was then greased to allow for easy removal after curing. After setting up the mold, soil was compacted in three layers with the hammer being dropped 56 times for each layer from a constant standard height. For the samples with geogrid however, geogrids were placed in the middle of the 2nd layer, on the top of the 2nd layer and in the middle of the first layer.
3. After the sample was compacted, it was left to cure at a safe place for either 7, 28 or 56 days as required as shown in Figure 2a.
4. After the sample was cured for the required number of days it was taken for testing where load was gradually applied vertically to it until it failed as shown in Figure 2b. The maximum load taken by each sample was displayed by the equipment and the results were recorded.

DOI: 10.55214/25768484.v9i2.4516

Figure 2.
(a) compacted samples placed for curing, (b) sample after compression test until failure.

3.4. CBR Test: Subgrade Evaluation

Figure 3 shows the minimum thickness of materials that is required above the chosen layer in a flexible pavement structure. The layers of materials in the pavement can be crushed stone, gravel, selected fill and subgrade. This study is focusing on the cover above the subgrade layer only. Figure 3a is for design of pavements that have high traffic, for example highways, whereas Figure 3b is used to design pavements that have low traffic, for example rural roads. Generally, subgrades have the lowest CBR followed by the fill, sub-base and base course materials. Hence, by increasing the CBR of the subgrade layer, theoretically there will be less materials required above it to achieve a similar level of overall pavement strength.

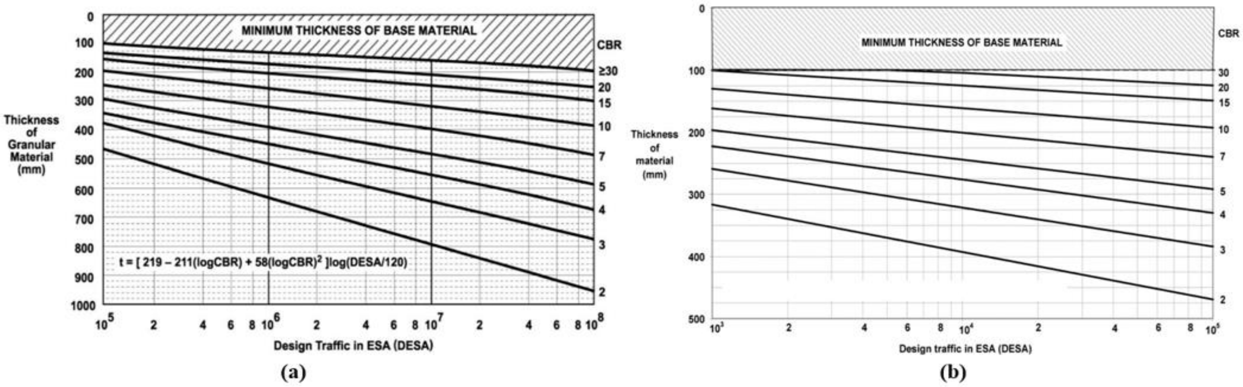

Figure 3.
Design chart used by Fiji Roads Authority (a) for flexible pavements [17] (b) for lightly trafficked flexible pavements [18].

4. Results and Discussion

The proctor test was conducted to deduce optimum moisture content of the soil. At this moisture content, soil has the most density when compacted to the standard amount of 25 blows per layer. Five trials of proctor tests were completed with varying moisture content, where trials 1 to 5 had moisture content ranging from 10% to 30% with intervals of 5%, as shown in Table 3. In Table 3, γ refers to the moist unit weight of the compacted soil sample, and γ_d refers to the dry unit weight of the compacted soil sample. For our clay soil sample, the maximum dry unit weight obtained from the graph was 12.09 kN/m^3 and its corresponding moisture content, which is the optimum moisture content, was 26%, as shown in Figure 4. This is the moisture content at which the soil possesses its greatest strength, and this is the moisture content that was used to condition the clay soil sample before every test. In the articles [8, 16, 19-22] the optimal moisture content for clay soil is around 25-30%, which confirms that our test was fairly accurate. In real life, subgrades and soil under foundations are tested using this method to optimize the compaction process, which leads to enhanced structural stability and durability. In the liquid limit test, the best fit line is drawn to find the moisture content which corresponds to 25 blows, which is 63% as shown in Figure 5. As seen from Figure 6, the shrinkage limit for this test was found to be 15%, whereas the plastic limit and liquid limit were 29% and 63% respectively. The purpose of conducting this test was to deduce the plasticity characteristics of the clay soil sample, and it is obtained by finding the moisture contents at which soil changes states, from solid to semi-solid, semi-solid to plastic, and plastic to liquid states. The shrinkage limit is the moisture content under which soil doesn't reduce in volume with reduction in moisture content. The plastic limit is the moisture content at which soil begins to change to a plastic state from a semi-solid state. Lastly, the liquid limit is the moisture content after which the soil begins to change to a liquid state from a plastic state. The shrinkage limit for the test was found to be 15%, whereas the plastic limit and liquid limit were 29% and 63% respectively, as shown in Figures 6 and 7. It was important that the optimum moisture content, found during the proctor test, lied in the semi-solid range. This was to ensure that the soil could be compacted to the optimal level. Consistency limit tests are crucial to find the soil plasticity and understanding the particular soil's behavior under different moisture contents and conditions.

Table 3.
Results of the proctor test.

	Moisture content, w (%)				
	10 %	**15 %**	**20 %**	**25 %**	**30 %**
γ (kN/m^3)	12.43	13.5	14.18	15.10	15.63
γ_d (kN/m^3)	11.3	11.74	11.81	12.08	12.02

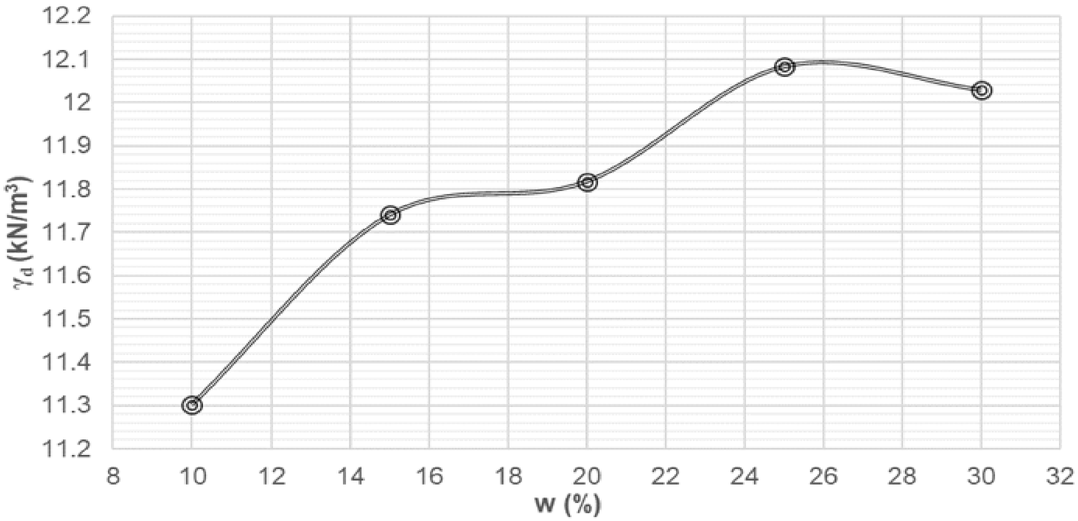

Figure 4.
Proctor test trials.

DOI: 10.55214/25768484.v9i2.4516

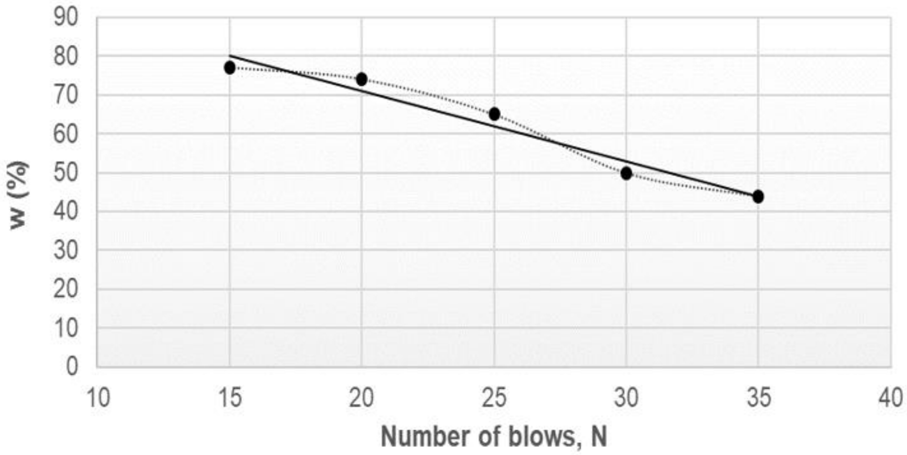

Figure 5.
63% moisture content corresponding to 25 blows.

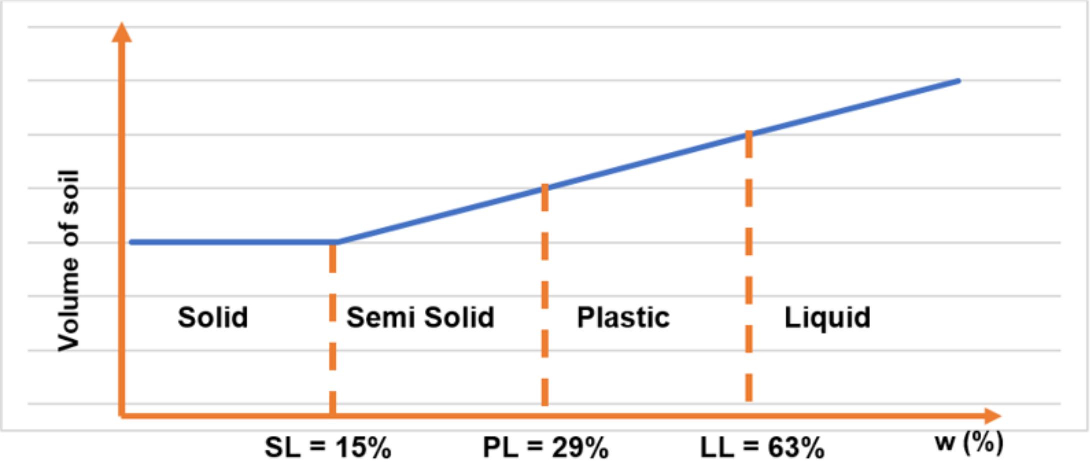

Figure 6.
Graph outlining the consistency limits of the clay soil sample.

4.1. California Bearing Ratio (CBR) Test

California bearing ratio (CBR) test is conducted to estimate the load bearing capacity of the clay soil sample. Generally, subgrades need higher bearing strength because they are under constant live loading. The CBR is found by calculating the ratio of the axial load at 2.5 mm and 5 mm penetrations for the sample being tested to the standard axial load at those penetrations, which is 697735 kg/m^2 and 1046603 kg/m^2 respectively for crushed stone. This study used a moisture content of 26% for all our soil samples and they were compacted in the CBR testing mold in 3 layers with 56 drops of hammer in each layer to achieve the required compaction. The fibres used were nylon, coir, and bamboo and all were 20 mm in length. These tests were conducted to determine the optimum fibre content and which fibres were effective in increasing the CBR of the soil samples. The CBR value for the unreinforced soil sample was 9.1%, whereas for the 0.5% fibre sample, the CBR values were 11.8%, 11.9%, and 12.3% for nylon, coir, and bamboo respectively, as shown in Table 4. It can be seen that the control sample had the lowest CBR value (9.1%), while the fibre reinforced samples had higher CBR values. For the 1% sample, the CBR values were 11.9%, 12.2%, and 12.4% for nylon, coir, and bamboo respectively. It was observed that samples with 1% fibre content had a higher CBR than samples with 0.5% fibre content, and hence for the second phase of CBR tests, 1% fibre content was used. For the second and third phases of CBR tests, jute fibres were used for nylon, as nylon had the least strength gain. The short fibres were added at 1% fibre content and three geogrids were placed in the middle of the 2nd layer, on the top of the 2nd layer and in the middle of the first layer of the CBR mold. The 1% jute, coir, and bamboo short-fibre reinforced samples had a maximum CBR of 11.57, 11.96 and 12.31 respectively, whereas the jute, coir, and bamboo geogrid reinforced samples had a maximum CBR of 11.58, 11.84 and 11.65 respectively. By comparing the CBR % values of the short fibre to the geogrid reinforced soil, it can be seen that short fibres have a greater effect in increasing the CBR of clay soil when compared to geogrids, as seen Table 5. This can be mainly because short fibres have the ability to interlock with the soil particles, increasing the resistance to deformation on a microscopic level, whereas geogrids are just sitting between adjacent layers of soil. Generally, CBR values for soft clays to rocks can range from 1% to over 100%. Table 6 shows the uses of soil corresponding to their CBR values. For subgrades, which is the bottommost layer in a road or runway pavement, the native soil is often enough to be used. However, if the soil rating is very poor, it is advisable to either reinforce it or to substitute it completely, and substituting native soil with new soil can be expensive. Soils which have a rating of fair are often used as subgrades and do not need to be reinforced. Moreover, if the CBR of the native soil can be more than 20%, then it can be even used in place of the base course, even more so if the CBR is closer to 50%. If the native soil has CBR from 30-50%, then less depth of material will be required in the pavement to achieve the same level of strength.

Table 4.
CBR values.

	Control	**0.5% Nylon**	**1% Nylon**	**0.5% Coir**	**1% Coir**	**0.5% Bamboo**
CBR %	9.14	11.8	11.9	11.9	12.2	12.3

Table 5.
CBR values of retested samples with 1% fibre content and geogrid reinforced samples.

Fibres at 1%	**Jute**			**Coir**			**Bamboo**		
Trials	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
CBR (%)	11.73	11.65	11.34	12.29	11.87	11.73	11.92	12.61	12.4
Average CBR (%)	11.57			11.96			12.31		
Geogrids CBR (%)	11.58			11.84			11.65		

Table 6.
General ratings of soils corresponding to various ranges of CBR values [23].

CBR (%)	**General rating**	**Users**	**Soil classifications (ASTM 2009)**
0-3	Very poor	Subgrade	OH, CH, MH, OL
3-7	Poor to fair	Subgrade	OH, CH, MH, OL
7-20	Fair	Subgrade	OL, CL, ML, SC, SM, SP
20-50	Good	Base, subgrade	GM, GC, SW, SM, SP, GP
>50	Excellent	Base	GW, GM
• OL – Organic silt • CL – Lean clay • ML – Silt • SC – Clayey sand • SM – Silty sand • SP – Poorly graded sand			The CBR for soil samples in this study falls between 7-20, which has a fair rating and can be directly used as a subgrade.

4.2. Direct Shear Test

The shear strength parameters of the control clay sample and reinforced samples are shown in Figure 7, where value of cohesion for each test is the y-intercept of the best-fit line for that respective test in kPa. The angle of internal friction is the angle the best-fit line makes with the horizontal and the peak shear strength is the highest point on the curve for each sample. The purpose of conducting this test was to deduce the shear strength parameters of the clay soil sample, which are the peak shear strength, cohesion (c), and angle of internal friction (φ). The peak shear strength represents the maximum shear stress the soil can resist before failure occurs. This test generates a shear stress-displacement curve that shows how the shear stress applied to the soil sample changes with increasing standard normal load, which is added at intervals. The standard normal loadings are 40 kg, 80 kg, and 120 kg, which correspond to effective normal stresses of 109 kPa, 218 kPa, and 327 kPa respectively. The normal loads are converted to effective normal stress by dividing the load values by the area of shear box. Normal stresses are responsible for increasing the shear strength of the soil by providing a vertical force to prevent the soil from sliding. Then the best fit line was inserted to indicate the Mohr-Coulomb failure envelope. The cohesion, c', values of the samples is given in Table 7, and these values represents the ability of the soil particles to mix and interlock with each other and is the shear strength of the soil independent of the applied normal stress. The tested samples had a relatively high cohesion which is true for clayey soils, and the values of cohesion increased with fibre reinforcement. The angle of internal friction, φ', quantifies the resistance of soil to deformation. It states the slope of the Mohr-Coulomb failure criterion for the tested soil sample. In the case of the control clay soil sample, it had a low angle of internal friction, which is true for cohesive soils such as clay [2]. However, the angle of internal increased slightly in the short fibre reinforced sample, and increased considerably more with the geogrid reinforced samples, as given in Table 7. This increase in angle of friction also has an effect on the peak shear strength can be seen in Figure 7. The peak shear strength, τ_f', is the maximum theoretical stress the soil mass can resist before failing in shear. The samples which had geogrids in them had far greater peak shear strength, 104.57 kPa (geogrid + short fibre) and 103.33 kPa (geogrid only) compared to the unreinforced and short fibre reinforced samples, 72.55 kPa and 79.23 kPa. This is mainly because geogrids were embedded vertically into the shear box and are much harder to deform in shear, as compared to short fibres, which are just mixed with the soil matrix. The direct shear test applications do not significantly affect subgrade applications, but more so to do with designing stable foundations, slopes, and retaining structures.

Table 7.
Cohesion, angle of internal friction, and peak shear strength of samples.

	Cohesion, c' (kPa)	**Angle of internal friction, φ'**	**Peak shear strength, τ_f' (kPa)**
Control	13.53	9.83	72.55
SF	15.92	11.36	79.23
Geogrid	16.52	14.87	103.33
Geogrid + SF	20.43	14.56	104.57

DOI: 10.55214/25768484.v9i2.4516

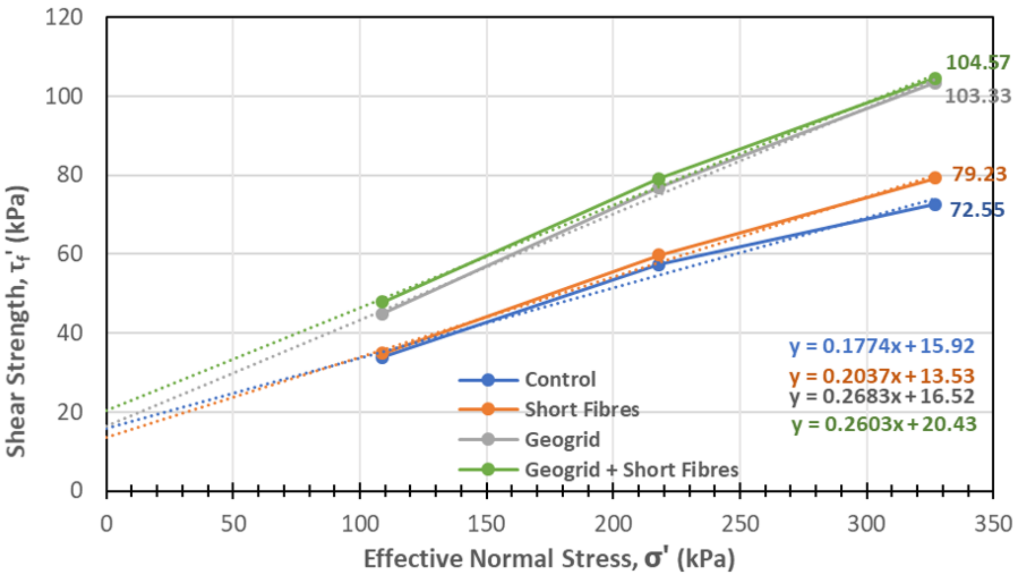

Figure 7.
Shear strength parameters for the control and reinforced clay samples.

4.3. Unconfined Compression Strength (UCS) Test

Figure 8 shows the compressive strength achieved through 2.5%, 5%, and 10% lime and cement addition to clay soil samples. This set of tests was conducted to find the optimum lime and cement content to be used for later tests. For both the lime and cement samples, there was a greater increase in strength from 2.5% to 5% chemical content, 0.689 MPa to 1.51 MPa for lime and 0.781 MPa to 1.76 MPa for cement, compared to the strength increase from 5% to 10%, 1.51 MPa to 1.92 MPa for lime and 1.76 to 2.22 MPa for cement. The graph also conveys that with increase in lime and cement content, the strength may further increase, but the increase from each interval may occur at reduced rate, for example, the percent compressive strength increase from 2.5% lime to 5% lime stabilized samples was 119%, whereas the percent compressive strength increase from 5% lime to 10% lime stabilized samples was 27%. Furthermore, Table 8 shows the differences in compressive strength between samples which had different fibre arrangements at 5% lime content. This set of tests was conducted to find the best fibre arrangement to be used for later tests. It can be seen that the sample which only had short fibres had the greatest compressive strength at 1.745 MPa, compared to the geogrid and geogrid + short fibre arrangements, which had 1.524 MPa and 1.675 MPa respectively. Hence, it was decided that the 7, 28, and 56 days cured samples will only have short fibre reinforcements with 5% lime and cement content. Moving on, Figure 9 shows the difference in strength from 7, 28, and 56 days cured samples. Two trials were conducted for each set of results and the average was taken as the compressive strength value. Both coir and bamboo fibres were used because they showed the highest strength increases in the CBR and direct shear tests. The best performing sample in the UCS test was the 5% cement and fibre reinforced samples which was cured for 56 days. It can be seen that the all the samples had an increase in compressive strength with increase in the curing period. All the samples had a similar percentage of strength increase at the 56 days curing period when compared to the samples that were cured for 7 days, with the greatest increase coming for the 5% lime and bamboo short fibre samples, which was 20.31% as shown in Table 9.

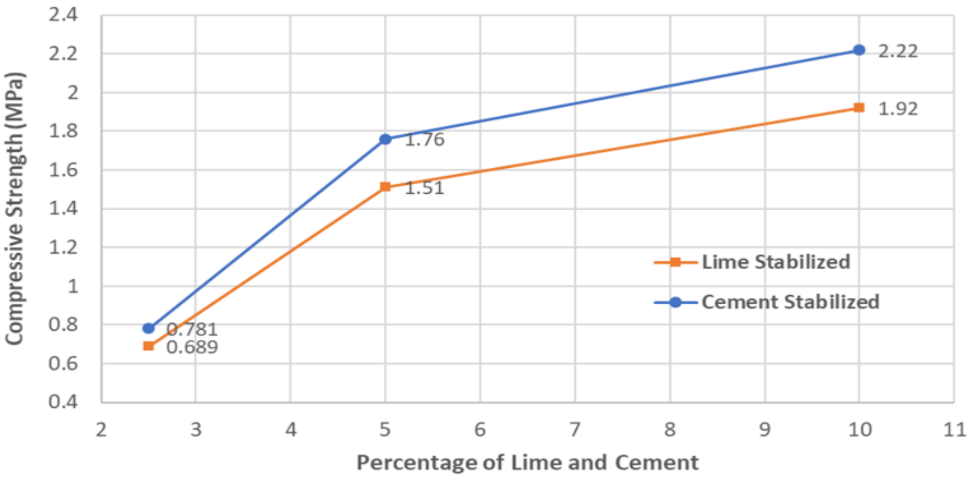

Figure 8.
Compressive strength of stabilized soil for different lime and cement content.

Table 8.
UCS test results for different fibre arrangements with 5% lime addition.

	Lime (5%) and cured for 5 days		
Fibre arrangement	**SF**	**Geogrid**	**Geogrid + SF**
Strength (MPa)	1.745	1.524	1.675

Table 9.
Final UCS test results for 7 and 28 days cured samples.

Chemical additive	**Lime (5%)**		**Cement (5%)**	
Fibre	**Coir**	**Bamboo**	**Coir**	**Bamboo**
7 Days cured strength (MPa)	1.95	1.92	2.07	2.12
28 Days cured strength (MPa)	2.12	2.14	2.28	2.24
56 Days cured strength (MPa)	2.27	2.31	2.41	2.46
(%) Strength increases from 7 days cured to 56 days cured samples	16.41%	20.31%	16.43%	16.04%

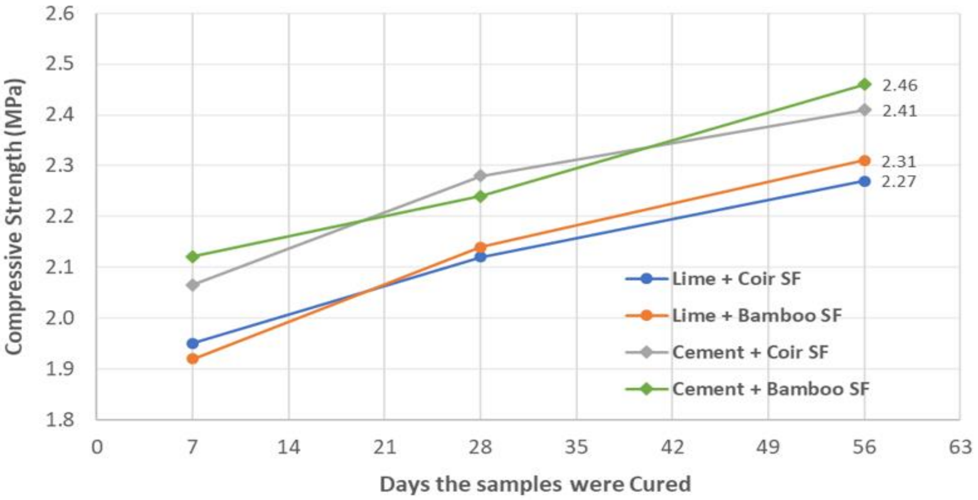

Figure 9.
Compressive strength of samples for different curing periods.

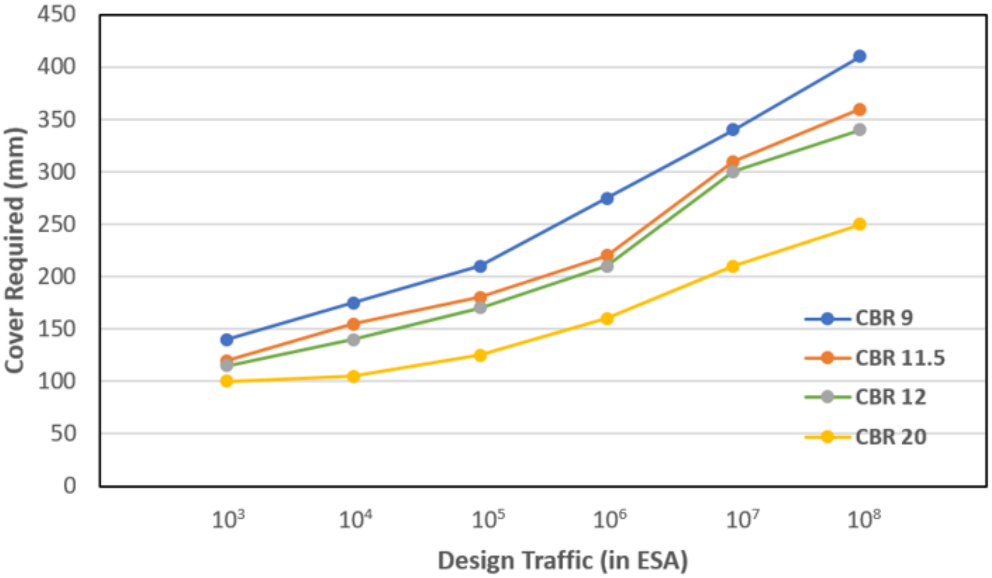

Figure 10.
Thickness of materials required corresponding to increasing CBR values.

4.4. Analysis on Subgrade Evaluation According to CBR and UCS Values

By using Figure 3, the thickness of materials (gravels and fills) required as a cover above the selected CBR (9, 11.5, 12, 20) subgrades was obtained. CBR 9 corresponds to the control sample, CBR 11.5 and CBR 12 were chosen because the fibre reinforced samples had most of the CBR values falling into these ranges, as seen in Tables 2 and 3. The Design traffic is used along with the CBR values to determine the cover, in mm, above the subgrade layer. It can be observed from Figure 10 that the higher the CBR value of the subgrade layer, the depth of material required as a cover under the same traffic load decreases. For example, the depth of material required as a cover for a subgrade of CBR 9 under 10^4 design traffic (ESA) load is 175 mm, whereas under the same traffic load a subgrade of CBR 12 will require 140 mm of cover. This means that overall, the volume of materials used as fills, sub-base and base course will decrease by 35 mm. The difference between the two values is just 35 mm of material, but looking at it from a road construction perspective, where there are kilometers of this subgrade and not forgetting the width of the lanes, there can be significant construction cost reductions.

Short fibres have performed the best in CBR and UCS tests but have come second in the direct shear test. As mentioned, geogrids perform better to resist shear stresses, which will be helpful in embankments and to resist earthquake loading, but moreover, they are important for other factors as well such as drainage. Thus, it can be said that in real large-scale applications, the combination of both short fibres and geogrids will result in better strength improvements.

5. Conclusions

Expansive soils pose significant challenges to civil engineering projects due to their high moisture induced volume changes, resulting in detrimental effects on foundations, structures, and infrastructure. This study investigated the effectiveness of utilizing bamboo, choir, nylon and jute fibres as stabilizers for expansive soil. The control soil was identified as well graded clayey sand, consisting of inorganic silts and organic clays, and classified as moderately-highly expansive. The CBR value of the control sample was also determined and it was concluded that it would be inadequate in road subgrade applications and would require significant stabilization.

- The maximum CBR reached through fibre reinforcement was 12.31 without the lime or cement addition.
- The maximum shear strength reached was 104.57 kPa, with the sample which had a combination of geo-grid and short fibres in the shear box, without the lime or cement addition.
- A maximum of 2.46 MPa of compressive strength was reached with the short fibre reinforced with 5% cement addition and cured for 28 days.
- The inclusion of fibres along with lime and cement resulted in a stronger subgrade compared to only using lime or cement, thus this is a more cost-effective solution to soil stabilization compared to just using lime and cement.
- The best performing fibre was bamboo fibre, both in terms of short fibres and geogrids. However, because coconut trees are as abundant in the pacific as bamboo, it can also be used because the decrease in performance is negligible and, in some cases, have proven to be stronger. Coconut trees are found in almost every part of Fiji and the pacific region, and through various strength tests it was seen that coir is just as capable in improving the strength of soil through reinforcement.
- The optimum percentage for the short fibres was determined to be 1% and the optimum fibre length was 20 mm. Moreover, for the use of geogrids, it should be distributed equally within the depth of the soil, and 20-30 cm between the layers should be sufficient. The geogrid layers proved to be beneficial for shear strength. The engineer responsible would have to calculate and estimate where the shear planes within the soil mass is and place this accordingly.
- The fibre content have a greater effect on the strength properties of clay soil than the length of fibres.
- A combination of short fibres and geogrids would be best for most applications such as road construction, seawalls and erosion control, and stabilizing slopes and embankments. Whereas in the case of foundations of buildings, it would be more suitable to use short fibres because there would be many inconsistencies in the foundation layout and the geogrids would have to be reconfigured several times.
- For chemical addition in stabilization, cement would provide greater strength for the same amount used, however, lime would be preferred since it provides similar strength improvements but more importantly, it is more environmentally friendly compared to cement since its production required less energy and produces less carbon dioxide than the production of cement.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Copyright:

References

[1] B. Freilich, C. Li, and G. J. Zornberg, "Effective shear strength of fiber-reinforced clays," presented at the 9th International Conference on Geosynthetics, Guarujá, Brazil, 2010.

[2] F. Tong, Q. Ma, and W. Xing, "Improvement of clayey soils by combined bamboo strip and flax fiber reinforcement," *Advances in Civil Engineering*, vol. 2019, no. 1, p. 7274161, 2019. https://doi.org/10.1155/2019/7274161

[3] P. M. Chaple and A. Dhatrak, "Performance of coir fiber reinforced clayey soil," *The International Journal of Engineering and Science*, vol. 2, no. 4, pp. 54-64, 2013.

[4] S. Amena and D. Chakeri, "A study on the effects of plastic waste strips and lime on strength characteristics of expansive soil," *Advances in Civil Engineering*, vol. 2022, no. 1, p. 6952525, 2022. https://doi.org/10.1155/2022/6952525

[5] S. M. Lakshmi *et al.*, "Enhancement of strength characteristics of clayey sand using fly ash and geonet," *Materials Today: Proceedings*, vol. 45, pp. 479-485, 2021. https://doi.org/10.1016/j.matpr.2020.02.078

[6] X. Yang, S. Liang, Z. Hou, D. Feng, Y. Xiao, and S. Zhou, "Experimental study on strength of polypropylene fiber reinforced cemented silt soil," *Applied Sciences*, vol. 12, no. 16, p. 8318, 2022. https://doi.org/10.3390/app12168318

[7] Y.-s. Shen, Y. Tang, J. Yin, M.-p. Li, and T. Wen, "An experimental investigation on strength characteristics of fiber-reinforced clayey soil treated with lime or cement," *Construction and Building Materials*, vol. 294, p. 123537, 2021. https://doi.org/10.1016/j.conbuildmat.2021.123537

[8] S. Akbulut, S. Arasan, and E. Kalkan, "Modification of clayey soils using scrap tire rubber and synthetic fibers," *Applied Clay Science*, vol. 38, no. 1-2, pp. 23-32, 2007. https://doi.org/10.1016/j.clay.2007.02.001

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

[10] Z. Huang, H.-Y. Sun, Y.-M. Dai, P.-B. Hou, W.-Z. Zhou, and L.-L. Bian, "A study on the shear strength and dry-wet cracking behaviour of waste fibre-reinforced expansive soil," *Case Studies in Construction Materials*, vol. 16, p. e01142, 2022. https://doi.org/10.1016/j.cscm.2022.e01142

[11] Y. Gong, J. Song, Y. He, and G. Ma, "Value coefficient of polyethylene fiber soil embankment slope based on response surface analysis," *Polymers*, vol. 14, p. 4295, 2022. https://doi.org/10.3390/polym14204295

[12] A. El Majid, C. Cherradi, B. Khadija, and Y. Razzouk, "Laboratory investigations on the behavior of CBR in two expanding soils reinforced with plant fibers of varying lengths and content," *Materials Today: Proceedings*, vol. 6, pp. 45-52, 2023. https://doi.org/10.1016/j.matpr.2023.06.395

[13] S. Tamassoki, N. N. N. Daud, S. Wang, and M. J. Roshan, "CBR of stabilized and reinforced residual soils using experimental, numerical, and machine-learning approaches," *Transportation Geotechnics*, vol. 42, p. 101080, 2023. https://doi.org/10.1016/j.trgeo.2023.101080

[14] D. Lal, N. Sankar, and S. Chandrakaran, "Effect of reinforcement form on the behaviour of coir geotextile reinforced sand beds," *Soils and Foundations*, vol. 57, no. 2, pp. 227-236, 2017. https://doi.org/10.1016/j.sandf.2016.12.001

[15] B. M. Das and K. Sobhan, *Shear strength of soil. In Principles of Geotechnical Engineering*, 10th ed. Boston: Cengage Learning, 2014.

[16] D. Vijayan and D. Parthiban, "Effect of Solid waste based stabilizing material for strengthening of Expansive soil-A review," *Environmental Technology & Innovation*, vol. 20, p. 101108, 2020. https://doi.org/10.1016/j.eti.2020.101108

[17] NZ Transport Agency New Zealand Government, "NZ guide to pavement evaluation and treatment design," Retrieved: https://www.nzta.govt.nz/assets/resources/NZ-guide-to-pavement-evaluation-and-treatment-design/Supplementary-notes-NZ-Guide-to-Pavement-Evaluation-and-Treatment-Design-Part-2.pdf 2024.

[18] Fiji Roads Authority, "Guid to pavement design: Supplement to the AUSTROADS guide to the structural design of road pavements," 2024.

[19] M. Salehi, M. Bayat, M. Saadat, and M. Nasri, "Prediction of unconfined compressive strength and California bearing capacity of cement-or lime-pozzolan-stabilised soil admixed with crushed stone waste," *Geomechanics and Geoengineering*, vol. 18, no. 4, pp. 272-283, 2023. https://doi.org/10.1080/17486025.2022.2040606

[20] A. Ghorbani and H. Hasanzadehshooiili, "Prediction of UCS and CBR of microsilica-lime stabilized sulfate silty sand using ANN and EPR models; application to the deep soil mixing," *Soils and Foundations*, vol. 58, no. 1, pp. 34-49, 2018.

[21] N. A. Saputra and R. Putra, "The correlation between CBR (California Bearing Ratio) and UCS (unconfined compression strength) laterite soils in palangka raya as heap material," presented at the Iop Conference Series: Earth And Environmental Science, San Francisco, 2020.

[22] S. K. Dash and M. Hussain, "Lime stabilization of soils: reappraisal," *Journal of materials in civil engineering*, vol. 24, no. 6, pp. 707-714, 2012. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000431

[23] BSI Standards, *Part 9: In-situ tests. British standard methods of test for Soils for civil engineering purposes.* Milton Keynes: British Standards Institution (BSI), 1990.

DOI: 10.55214/25768484.v9i2.4516