

UNCONFINED COMPRESSIVE STRENGTH OF CLAY REINFORCED WITH KEROSENE-TREATED COIR FIBER

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ABSTRACT: The need for ground modification is more prevalent as the availability of good site conditions decrease. Among the available methods of ground modification, soil reinforcement is emerging as a promising alternative. Fiber reinforcement involves mixing fibers with soil to improve its strength characteristics. Natural fibers have the following advantages over synthetic: affordability, bulk availability, and eco-friendliness. Coir fiber has the greatest tensile strength and slowest rate of biodegradation among natural fibers. This study presents the effect of kerosene-coated coir on strength and stress-strain response of a cohesive soil. Preliminary soil tests were performed and the soil was classified as CH or high-plasticity clay. Water absorption capacity tests revealed that kerosene reduces moisture intake of coir by up to 170%. Reconstituted samples, with fiber concentrations ranging from 0% to 2% by dry weight of soil, were tested for unconfined compressive strength in optimum moisture and dry states. Results showed that incorporation of coir improved the strength and stress-strain response of high-plasticity clay by as much as 52% compared to unreinforced samples. Aside from increasing peak strength, addition of coir also improved the post-peak behavior of the samples. Results show improved ductility in the coir-reinforced samples tested at optimum moisture condition. An increase in the elastic modulus, by as much as 78%, was also observed. These improved performance was exhibited at 1.5% fiber content.

Keywords: Soil reinforcement, Coir fiber, Clay reinforcement, Ground modification

1. INTRODUCTION

Ground modification refers to a variety of techniques used to improve the engineering characteristics of the ground. It can be used in various soil conditions such as collapsible soils, expansive soils, soft soils, or soils with inadequate mechanical properties. One method of modifying the ground is the use of reinforcing elements in the form of strips, bars, sheets, membranes, and fibers.

Fiber reinforcement involves mixing natural or synthetic fibers with soil, where the fibers act as tensile resisting elements that improve soil strength. The primary advantages of natural fibers are that they are cheap, abundantly available, and biodegradable. In the Philippines, the locally available natural fibers include abaca, coir, banana, pineapple, and bamboo. Among these natural fibers, coir has the greatest tensile strength and has the slowest rate of biodegradation [1]. Coir is useful in practical applications as a geotextile material. The fibers are twined and woven into “coco nets” which are primarily used for erosion control. Other coir products include coir mattresses, coir tufted mats, coir ropes, and coir logs.

The Philippines, being a tropical country, is abundant in coconut trees. In 2015, the Philippine Coconut Authority reported a total of 3.517 million hectares planted with coconuts in the

country. This area is also 26% of the country’s total agricultural land. The average nut production is 14.902 billion nuts/year.

In the context of sustainable development, coir fiber is a promising soil reinforcement material because it is indigenous, abundantly available, cheap, and environment-friendly. It can be a cost-effective alternative to commercially available additives such as cement and lime. Coir fiber reinforcement can be used in cases where mixing with fibers can be done onsite, such as in pavement subgrade, small embankments, and engineered fill. Processing of coir contributes to rural employment and income generation. Large-scale utilization of coir can expand the market for the country’s coir industry.

Lastly, there is a need to find a suitable treatment method that will increase the life span of coir fibers. To serve its intended purpose as soil reinforcement for a longer duration, a protective coating may be required. Coir, just like any natural fiber, gradually loses strength over time. Depending on the duration of use, it may require a physical coating to protect it from moisture-induced degradation. In this context, this paper presents the results of an experimental investigation on the effect of coated coir fiber reinforcement on the strength and stress-strain response of local clayey soil.

The primary objective of the research is to study the effect of kerosene-coated coir fiber reinforcement on the strength of clayey soil. To attain this, it is necessary to investigate effect of kerosene coating on water absorption capacity of coir, examine effect of coir on the unconfined compressive strength of soil and the soil stress-strain response, and, evaluate effect of coir on soil samples tested at optimum moisture content and dry state.

2. FIBER REINFORCEMENT IN SOIL

Hausmann [2] classified ground modification techniques into four: mechanical modification, hydraulic modification, physical and chemical modification, and modification by inclusions and confinement. Mechanical modification involves increasing the density of soil by compaction, which requires mechanical energy. This is achieved through plate vibrators, impact rollers, and special techniques like vibro-flotation and blasting. Hydraulic modification involves removal of pore water from the ground using vertical drains or wells. Physical and chemical modification is the use of additives mixed or blended with soil. Natural soils, cement, fly-ash, and limestone are some examples of soil additives. Modification by inclusions and confinement is the use of strips, meshes, bars, fabrics, and fibers to reinforce the soil.

Soil reinforcement by inclusions has the ability to improve strength and stability, reduce settlements, improve bearing capacity, and reduce lateral deformation [3]. One method of reinforcing soil is with the use of fibers. Nature provides an example of this in the roots of trees stabilizing near-surface soil with low shear strength. The roots are distributed randomly within the soil mass and act as tension members to improve the strength characteristics of the soil [4].

The stabilizing effects of plant roots may be replicated artificially with the use of natural or synthetic fibers. Randomly distributed fibers (RDFs) are mixed with soil in the same manner as an additive. Unlike traditional geosynthetics, they are not oriented in a specific direction. The main advantages of RDFs are the relative isotropy of the soil mass and the absence of predefined planes of weakness [5].

2.1 Fiber

Shukla [4] defines fiber as a unit of matter characterized by fineness, flexibility, and high ratio of length to diameter. Fibers fall under two categories: synthetic and natural. Examples of synthetic fibers are glass fibers, polypropylene (PP) fibers, polyester (PET) fibers, polyethylene

(PE) fibers, metal fibers, carbon fibers [4]. Natural fibers include coir, jute, palm fibers, sisal fibers, bamboo fibers, banana fibers, manila fibers, and cotton fibers.

The advantages of natural fibers are strength, bulk availability, affordable cost, and environmental-friendly characteristics. Unlike synthetic fibers, natural fibers do not contribute to greenhouse gas emissions in construction. Some practical disadvantages of natural fibers are variability of the fiber geometry and biodegradability. Most natural fibers except coir are not durable in alkaline environments. Natural fibers exhibit gradual loss of strength over time, with rate of strength loss varying across fiber types [4].

2.2 Fiber Treatment

The issue of biodegradability can be overcome by suitable fiber treatment methods. These modification techniques can make natural fibers on par with or even superior to synthetic fibers. Unnikrishnan [6] provides some possible treatment methods for natural fibers. These are alkali treatment, enzyme treatment, UV grafting with monomers, treatment using chemicals, natural anti-microbial finishing, vegetable oils, and physical coatings. Physical coatings modify the surface of fibers using synthetic polymers or resins. By physically preventing the entry of moisture into the fiber, this technique improves the durability of natural fibers [6]. A study by T. Sanyal and K. Chakraborty [7] found that bitumen coating applied on jute geotextiles could defer degradation by 3 to 4 years. However, bitumen affects the flexibility and drapability of the geotextile. H.N. Ramesh and K.V. Manoj Krishna [1] conducted water absorption studies on coir coated with kerosene, bitumen, and varnish. After 365 days of submergence, kerosene and bitumen coated coir fibers showed decreased water absorption, with kerosene providing the highest reduction in moisture intake compared to uncoated coir. Varnish, on the other hand, did not exhibit significant difference

2.3 Coconut Coir as Soil Reinforcement

Coir has the greatest tensile strength of most natural fibers [4]. It contains 40% lignin and 54% cellulose [9]. Its high amount of lignin, a complex hydrocarbon polymer, is what makes coir degrade slower than other natural fibers. Lignin makes the stem rigid and protects the fiber against biological attack [6]. Coir fibers may be used in engineering applications for a period of 1 to 2 years [4]. Several researches have investigated coir as randomly distributed fiber on different types of

soil. Laboratory tests including triaxial tests, unconfined compression tests, and California bearing ratio tests showed significant results on the effect of coir inclusion.

Sujatha et al. [10] studied the influence of randomly distributed coir fiber on the compaction characteristics, stress-strain behavior, and unconfined compressive strength of highly compressible clay. The soil sample has a liquid limit of 53 and plasticity index of 38. Compaction tests were performed to determine the optimum moisture content (OMC) and maximum dry density (MDD) of unreinforced and reinforced samples. The study showed that OMC increased and MDD decreased with the inclusion of coir. The increase in OMC was attributed to the tendency of coir fibers to absorb moisture. Replacement of fibers in the soil matrix caused a decrease in mass occupied in the standard volume, explaining the decrease in MDD.

Unconfined compression tests were carried out to determine the effect of coir fiber on stress-strain behavior and unconfined compressive strength of the soil sample. Four fiber concentrations were studied: 0%, 0.25%, 0.5%, 0.75%, and 1%. Addition of coir fiber resulted to an increase in unconfined compressive strength, with the optimum fiber content being 0.75%. Beyond 0.75%, clumping of fibers was observed and resulted to a decrease in strength. Figure 1 shows that stress-strain of soil shifted to a more plastic behavior.

Devdatt et al. [11] made an experimental study on expansive soil mixed with varying concentrations of coir (0% to 1%). Results of compaction tests revealed a decreasing trend in OMC and increasing trend in MDD with addition of coir. Soaked and unsoaked California bearing ratio (CBR) tests were also conducted. Results exhibited a linearly increasing trend in both soaked and unsoaked CBR value. A similar study by Peter et al. [12] investigated the behavior of soft soil stabilized with varying concentrations of coir pith (0% to 3%) and coir fiber (0% to 1%) by conducting California bearing ratio (CBR) tests and static triaxial tests. The optimum stabilization scheme found in the study was 2% coir pith and 6% short coir fiber, which exhibited the greatest improvements in CBR value. Stress-strain curves from triaxial testing revealed a more ductile behavior in the coir-stabilized sample. The combined treatment of coir pith and fiber also increased the elastic modulus by 1.74 MPa.

In a study by Sivakumar Babu, G.L. and Vasudevan, A.K. [13], the effect of coir fiber parameters on strength and stiffness of sandy soil was studied. Triaxial tests were performed for varying confining pressures, fiber lengths, fiber contents, and fiber diameters. Fiber contents varied

from 0% to 2.5% by weight of soil. Test results showed that deviator stress at failure increased as the fiber content increased. This was observed in all variations of confining pressures. The optimum coir content corresponding to the maximum strength improvement was at 2% to 2.5%. The researchers also noted that preparing specimens beyond 2.5% fiber content was quite difficult. Coir fibers grouped according to diameter (0.15, 0.25, and 0.35 mm) were also tested to observe the effect of fiber diameter on strength of soil. For both confining pressures of 50 and 100 kPa, the deviator stress at failure increased with increasing fiber diameter. This was attributed by the researchers to the increase in pullout resistance for fibers with larger diameter.

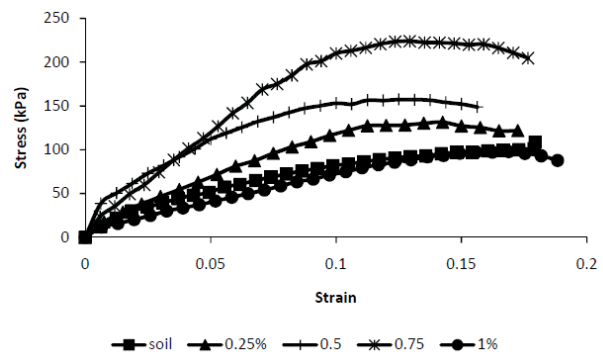


Fig.1 Stress-strain Plots of Unreinforced and Coir-Reinforced Samples [11]

Fiber diameter and content was also kept constant while lengths were varied (10, 15, 25, and 30 mm). The maximum strength improvement was exhibited by samples with 15 mm fibers. Short fibers (10 mm) have less area in contact with soil, resulting to less pullout resistance and less strength gain. Preparing samples with longer (30 mm) fibers was reported to be difficult, making them ineffective as reinforcements.

Another experimental investigation on the use of coir for improving expansive black cotton soil measured the degree of improvement in strength, shrinkage, swelling, and compressibility due to addition of fibers [14]. Length of coir fibers were kept at 15 mm, since this was the optimum length found in Sivakumar Babu and Vaseduvan's related study on coir-fiber reinforced sand.

Test results revealed the following: (1) deviator stress at failure increased with increasing fiber content; (2) deviator stress increased with increasing fiber diameter; (3) cohesion and friction angle increased as fiber content increased; (4) coir fibers reduced soil swell potential and compression index. The study concluded that coir as randomly distributed fiber contributes significant improvement in expansive black cotton soils.

Another study by Dasaka and Sumesh [15] evaluated the effect of coir on the stress-strain response of a reconstituted fine-grained soil. Unconfined compression tests and unconsolidated-undrained (UU) triaxial tests were performed using fiber contents in the range of 0% to 2% by dry weight of soil. Results of the study show that unconfined compressive strength (UCS) increased with increase in fiber dosage. At 1.5% fiber content (optimum), the UCS of reinforced soil is more than twice that of unreinforced soil. However, the study also found that UCS of soil reinforced with 30-mm length fibers is less than that of unreinforced soil. The researchers recommend using 15 mm fiber lengths when forming 38 mm-diameter soil specimens.

From triaxial test results, it was found that peak deviator stress and major principal stress at failure increased with increase in fiber dosage for all confining pressures. Cohesion and friction angle both increased significantly. Cohesion achieves maximum value at 1.5% fiber content. Friction angle, on the other hand, steadily increased with increase in fiber content. Researchers also noted an overall shift to ductile behavior in the stress-strain response of coir-reinforced samples.

In both UCT and UU triaxial tests, addition of coir fiber in the range of 1.5% to 2% was reported to produce significant improvement in the soil. Fiber dosages less than 1.5% exhibit minimal strength improvement. For dosages greater than 2%, specimen preparation becomes too difficult because of fiber agglomeration.

Ramasubbarao [16] investigated the effect of kerosene-coated randomly distributed coir fibers on highly compressible clay. Using fiber length of 5 mm and varied fiber contents (0.5%, 1%, and 1.5%), the optimum coir content was found to be 1% based on peak compressive strength. Stress-strain response shifted from brittle to a more ductile one with addition of coir. The researcher also performed water absorption capacity tests on uncoated and coated fibers, where it was found that kerosene coating significantly reduced the moisture absorption of coir.

3. METHODOLOGY

The research focused on soil improvement with respect to unconfined compressive strength. Initial steps were acquisition and preparation of the soil samples, kerosene, and coir. Local clayey soil used in the study was obtained from Sikatuna Village, Quezon City. Coir fibers were obtained from a small-scale farm in Dolores, Quezon. Preliminary soil tests were conducted on oven-dried soil for classification purposes. All tests are performed according to ASTM standards. Coir fibers were cut to a fixed length and coated with kerosene. Coated

and uncoated fibers were subjected to water absorption capacity tests. Standard proctor test provided the maximum dry density and optimum water content of the soil sample. Coated fibers were added to soil in varying concentrations. Reconstituted samples were prepared using the soil-fiber mixes. The orientation of the fibers due to the soil mixing process cannot be controlled.

Unconfined compression tests were conducted on soil samples at optimum moisture condition. Stress-strain plots were generated and compressive stresses at maximum load were obtained. Statistical analysis was performed on the data to determine the optimum fiber concentration. The long-term performance of coir fibers as reinforcement was not investigated.

4. RESULTS AND DISCUSSION

4.1 Soil Analysis

Laboratory tests were performed for characterization of the soil sample. The tests include sieve analysis, Atterberg limits tests and standard proctor test. Results of the said tests were used to classify the soil sample according to the Unified Soil Classification System. Table 1 shows the results of the tests performed.

Table 1 Index properties of soil sample used

Soil Property	Soil Sample
Passing #4 sieve	99.97%
Passing #10 sieve	94.45%
Passing #20 sieve	85.23%
Passing #200 sieve	53.68%
Liquid Limit	80
Plastic Limit	35
Plasticity Index	45
USCS	CH
Max. Dry Unit Weight	12.05 kN/m ³
Optimum Moisture Content	31.15%

4.2 Fiber Testing

Water absorption capacity tests were carried out to determine if a physical coating can help defer the degradation of coir by reducing moisture intake. Figure 2 illustrates the effect of kerosene coating on the water absorption behavior of coir. It is evident that kerosene-coated fibers have significantly lower water absorption level than uncoated fibers. There is also a steep increase in water absorption at the beginning of the test. As immersion time increased, water absorption capacities leveled off, approaching equilibrium.

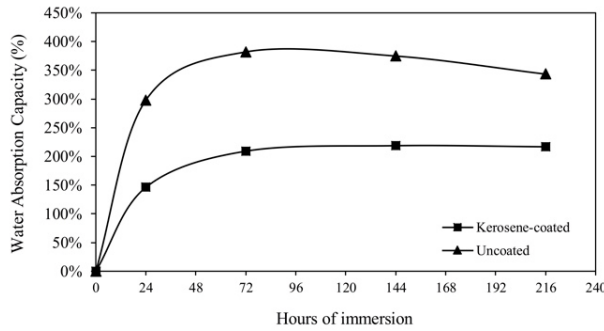


Fig.2 Effect of Kerosene Coating on Water Absorption Capacity of Coir

4.3 Unconfined Compression Strength

A total of 25 reconstituted samples of unreinforced and reinforced clay were tested for unconfined compressive strength immediately after preparation. The samples after failure were oven-dried to determine water content. Table 2 presents the average values of maximum load and its corresponding compressive strength at maximum load and water content for each fiber concentration.

Table 2 Mean values of maximum load for each fiber concentration

Fiber Concentration (%)	Average Max Load (N)	Stress at Max Load (MPa)	Water Content (%)
0	264.65	0.132	34.50
0.5	303.75	0.150	33.08
1.0	371.74	0.183	34.09
1.5	406.06	0.200	32.98
2.0	320.69	0.158	33.75

From Figure 3, it can be observed that strength of reinforced samples has significant difference from that of unreinforced samples. This can be said for all fiber concentrations. Furthermore, the maximum strength improvement was seen in the 1.5% coir-reinforced group. It also shows that compressive strength values increased as fiber content increased. At the optimum fiber content of 1.5%, average unconfined compressive strength was increased by 52% compared to plain samples. The strength increase can be attributed to the pull-out resistance of the coir fibers during compression.

Sample preparation at 2% fiber content was made difficult by the clumping of coir fibers. Failure mostly occurred in the weak regions of the samples where fiber agglomeration was observed. This explains the decrease in strength from 1.5% to 2% fiber concentration. Still, samples with 2% coir exhibited higher compressive strength than unreinforced samples.

Typical results of the stress versus strain

response for various fiber concentrations are presented in figure 4. Resulting stress-strain curves for the 25 samples are shown in figure 5.

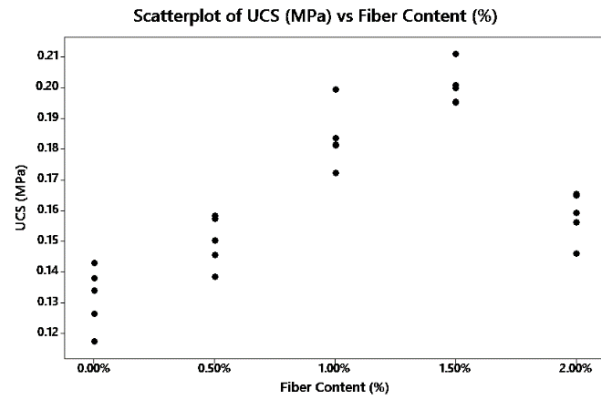


Fig.3 Plot of the compressive strength obtained for each samples

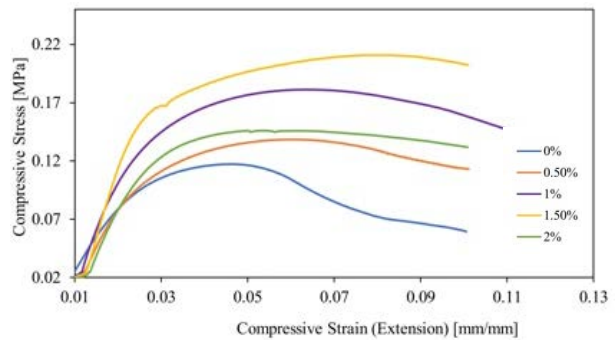


Fig.4 Typical Stress-strain Curve of Soil for Different Fiber Concentrations

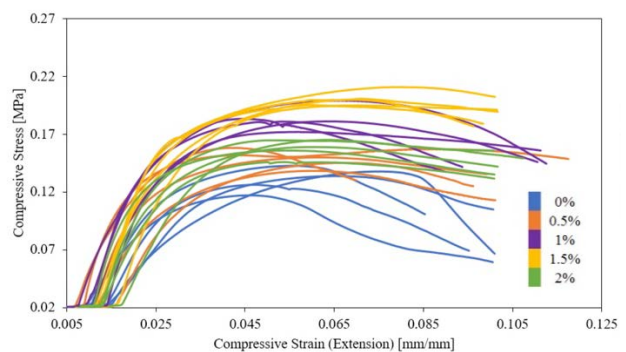


Fig.5 Stress-strain Curves of Soil for Different Fiber Concentrations

Peak strengths for all the samples occurred at about 4% to 7% strain. Aside from increasing peak strength, coir fiber reinforcement was also found to improve the post-peak behavior of the soil. Compared to plain samples, coir-reinforced samples exhibited less reductions in strength after peak. Soil with coir behaved more like a ductile

material.

The elastic moduli of all the samples were obtained by from the stress-strain curves. The mean values are presented in Table 3.

The same trend in the case of peak compressive strength was observed in the elastic modulus of the groups. Values steadily increased from 0% to 1.5%, where the maximum improvement was observed. Addition of 1.5% coir resulted to a 78% increase in elastic modulus compared to plain soil. At 2% coir, there was also a decrease from the maximum value seen at 1.5% coir.

Table 3 Mean elastic moduli for different fiber concentrations

Fiber Concentration (%)	Elastic Modulus (MPa)
0	5.73
0.5	8.34
1	9.94
1.5	10.21
2	8.09

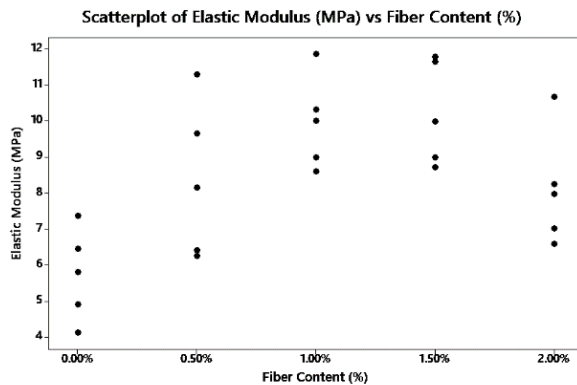


Fig.6 Elastic modulus of samples with different fiber content

4.4 Failure Patterns

Figure 7 presents the failure patterns of samples under unconfined compression test.

A well-defined shear plane was observed in the 0% and 0.5% reinforced samples. In contrast, samples with 1% and 1.5% coir exhibited bulging failure and formation of small cracks. The samples at the optimum fiber content showed minimal signs of failure compared to plain samples. As the fiber content increases, failure would happen slowly and the sample behaves like a ductile material. The increased ductility due to fiber reinforcement allows the samples to bear stress even after peak. At 2% fiber content, it was observed that failure mostly occurs in the regions where fiber has agglomerated, contributing to the lower compressive strength.

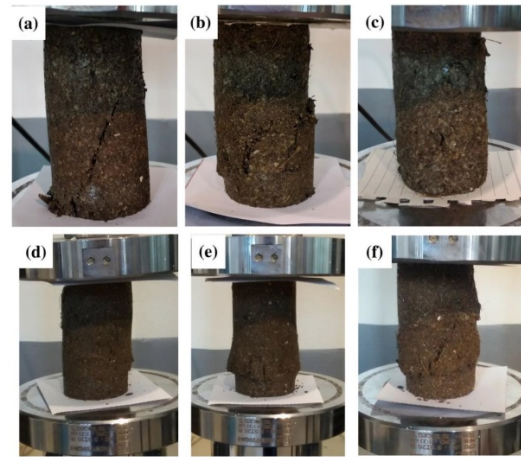


Fig.7 Typical Failure Patterns: (a) 0%, (b) 0.5%, (c) 1%, (d) 1.5%, (e) 1.5%, (f) 2%.

5. CONCLUSIONS

The present study investigated the effect of kerosene-coated coir fiber on strength and stress-strain characteristics of a reconstituted cohesive soil sample. The soil sample was classified as high-plasticity clay and found to have a maximum dry density of 12.05 kN/m³ and optimum moisture content of 31.15%. The use of kerosene as protective coating significantly lowers the water absorption capacity of coir by up to 170%. It was proven to be an effective protective coating to reduce moisture-induced coir degradation.

Coir fiber reinforcement was found to be beneficial to clayey soil. The maximum strength improvement was at 1.5% fiber content, with a 52% increase in strength compared to unreinforced soil. However, fibers tend to clump together at fiber concentration of 2%, resulting to a decrease in strength from the average strength at 1.5%. Still, 2% reinforced samples have higher compressive strengths than samples with 0% coir. Addition of coir fiber limited post-peak strength reduction in the soil. From the stress- strain graphs, it was observed that samples with coir exhibited improved ductility. A 78% increase in soil elastic modulus was also observed at the optimum fiber content. Well-defined shear failure planes were seen in the 0% and 0.5% samples. At higher fiber concentrations, failure occurs slowly and minimal signs of failure were observed.

6. RECOMMENDATIONS

The researcher recommends that experiments can be conducted to determine the effectiveness of kerosene coating on preserving coir fibers under buried conditions over a long period of time. Furthermore, tensile strength tests can be performed to determine if kerosene has any effect

on coir tensile strength. It is also suggested to know the applicability of coir on other soil types such as silts and sands may also be studied. For a more in-depth experimental study, shear strength tests such as triaxial compression tests and direct shear tests may be used to evaluate coir as soil reinforcement. California bearing ratio tests may be used to determine the effect of coir on weak subgrade. Swell index tests may also be done for expansive soils mixed with coir. The effect of varying coir fiber parameters (e.g. length, diameter) on the strength improvement may also be further studied. Additionally, regression models may be proposed to quantify the effect of fiber parameters on the shear strength of soil.

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