

**EFFECT OF CASHEW NUT SHELL LIQUID
ON COIR REINFORCED SOIL – AN
EXPERIMENTAL INVESTIGATION**

A DISSERTATION

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FOR THE DEGREE
OF

MASTER OF TECHNOLOGY
IN
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Submitted by:

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CANDIDATE'S DECLARATION

I, **B. VISHALA REDDY, Roll No: 2K24/GTE/02** student of M. Tech (Geotechnical Engineering) , hereby declare that the project Dissertation titled “EFFECT OF CASHEW NUT SHELL LIQUID ON COIR REINFORCED SOIL – AN EXPERIMENTAL INVESTIGATION” which is submitted by me to the **Department of Civil Engineering, Delhi Technological University, Delhi** in the partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work was not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled “EFFECT OF CASHEW NUT SHELL LIQUID ON COIR REINFORCED SOIL – AN EXPERIMENTAL INVESTIGATION” which is submitted by **B. VISHALA REDDY, Roll No: 2K24/GTE/02** Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the Degree of Master of Technology, is the record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

Weak soils frequently require stabilization to meet the increased strength and durability demands of their intended applications. Such porous soils are widely distributed across Northern and Southern India. During road construction, enhancing the strength of weak subgrades is crucial, as this directly influences both the required thickness and the overall service life of the pavement. We engineers have to minimize pavement thickness to lower the construction cost and conserve conventional building materials for enhancing the stability of subgrade soil, using coconut fibre for this enhancement is highly an advantage since it offers economical, ecofriendly, efficient and accessible characteristics. Bio-degradable fibres act as a super alternative for soil stabilization but also comes with challenges. One of those challenges is its susceptibility to biodegradation and Hydrophilic nature which restricts its broader application in geotechnical engineering.

Nevertheless, this challenge can find a solution in modifying the fibre surface with proper chemical treatment which converges with sustainability. This research studies the effect of treating the coil fibres with cashew nut shell liquid, an affordable agricultural by product. Hence coating these fibres with natural biopolymer that is CNSL renders the surface into hydrophobic thereby reducing moisture and fungal or microbial attack. This

enhances the durability of the fibre and long-term retention of the subgrade. The study evaluates the engineering properties of the soil (poorly graded sand (SP)) reinforced with coir fibre and CNSL coated coir fibre. Laboratory tests including Proctor, Direct shear and CBR were performed using 3cm long coconut fibre with varying percentages (0.1%, 0.2%, 0.3%).

Compaction tests across different fibre contents established the specific characteristics of the compaction curves, while Direct Shear tests analysed the comparative strength profiles. Results indicated that untreated fibres, owing to their lightweight nature and higher water absorption capacity, exhibited a higher optimum moisture content (OMC) and a lower maximum dry density (MDD) than the CNSL-treated variants. The shear strength parameters of the reinforced soil samples were quantified through apparent cohesion and the interface friction angle. Experimental findings demonstrated that CNSL-treated coir geotextiles significantly enhanced these interface shear strength parameters. Ultimately, the CNSL coating diminished the interaction between the fibres and water, thereby effectively decelerating the biological degradation process of the coir material.

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LIST OF ABBREVIATIONS

IS	Indian Standard
ASTM	American Society for Testing and Materials
CNSL	Cashew Nut Shell Liquid
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
TCF	Treated Coir Fibre
USCS	Unified Soil Classification System
CuSO ₄	Copper Sulphate
HNO ₃	Nitric Acid

LIST OF SYMBOLS

γ	Unit weight of soil
ϕ	Angle of internal friction
e	Void ratio
D_{10}	Effective particle size
c_a	Apparent cohesion
c	Cohesion
τ	Shear stress of soil
δ	Interface friction angle
(σ_d / ϵ)	stiffness modulus

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The integration of sustainable materials into geotechnical engineering is becoming increasingly prevalent as concerns for environmental health and future generations grow. Given the ecological challenges linked with traditional synthetic materials such as steel, cement, ash, and plastic composites there is a pressing need for alternative geotechnical approaches. Consequently, natural fibres have gained significant traction over synthetic options as a viable soil-reinforcement strategy within sustainable geotechnics. The practice of utilizing natural fibres for soil stabilization is experiencing rapid growth across the civil engineering sector.

A subgrade serves as the foundational structure, composed of natural or imported soil, upon which subsequent granular pavement layers such as the sub-base, base, and surface courses are constructed. Quality of this subgrade is key to the performance and efficiency of any roadway. Roadways with low volume within rural areas facilitate connectivity and social improvement of these communities between large urban centers and a smaller rural population. But these are less populated roads and are generally constructed to inferior requirements than the highways of importance. Most tend to be unsurfaced or otherwise called 'mud roads' with a subgrade topped with a subbase layer up to 150 mm thick. Local sandy soils are also limited in the application of this, whose fine-based small quantity of particles and non-cohesion also contribute to poor unconfined shear strength and therefore, are not suitable for load-bearing purposes, such as road subgrades, when local sandy soils are employed. Should this sand be accidentally

deposited beneath pavements or recreational surfaces without proper stabilization or confinement, repeated loading leads to large-scale displacement, structural deformation and surface depressions. On the one hand, sandy soil generally has an increased drainage to prevent waterlogging. This reduces resistance to rutting and erosion under dynamic traffic loading. In the absence of sufficient compaction, binders or confinement, they may expand to develop loose spaces, which then give rise to localized settlement areas and hence decrease both surface performance and long-term stability. Sands often need stabilization to reach the additional strength and durability that their structural uses require. Thus, in the current analysis, the effectiveness of uncoated and coated coir fibres as soil reinforcing materials for soil construction was examined and compared for enhancing basic soil engineering properties.

In reinforced soil science, there is an accelerated progression toward sustainable, evidence-based options. Traditional synthetics in reinforcement decompose very slowly, leading to longer-term environmental pollution. Natural fibres can replace these artificial materials since there is a relatively low density, certain strengths and also a greater green potential of natural fibres resulting in reduced energy consumption and lower emissions from manufacture. However, the natural fibres represent a unique problem, since the high moisture affinity promotes microbial community growth that ultimately destroys the material and reduces the fibre adhesion. Addressing these natural fibres with suitable water-resistant agents that can reduce water absorption at the fibre-matrix connection, such as bio-resins, asphalt emulsions, paints, or a mixture of rosin-alcohols, are useful. This treatment improves the toughness of the reinforcing fibre and increases the subgrade strength of the reinforced fibres, thus improving the lifetime of the pavement.

1.2 SAND

Mainly from the Yamuna River basin and surrounding alluvial plains, it is a type of sand used in Delhi's school playgrounds. Displaying a light yellow to pale brown hue, it comprises mainly quartz grains with some trace feldspar and mica components. Geotechnically, this soil can have little cohesion, high porosity, and a good drainage ability; in this form, the ground is quick to percolate surface water. With its poor nutrient

profile and low water-retention qualities, it is unfit for agricultural use; however, these same properties provide it significant suitability for playground surfaces.



Figure 1: Sand

It serves as a cushion and absorbs impact, effectively preventing waterlogging for athletic activities on the play surface. Physically the sand is non-plastic and initially loosely packed, but eventually in-situ becomes compacted by its regular application. Formed under semi-arid to sub-humid environments, the material is dry year-round and absorbs heat quickly in summer. To ensure strength and comfort for users, the sand layers are usually erected between 10 cm-30 cm deep over a compacted soil footing.

1.3 NATURAL FIBRES

Natural fibres consist mainly of lignin, pectin, hemicellulose, and cellulose. The differences in the relative proportion of the constituent molecules from fibres directly influence their characteristic properties. In this structural matrix, cellulose is the most rigid organic component. Hemicellulose maintains hydroxyl and acetyl functional groups to provide an intrinsic hygroscopicity to the compound. The overall lifetime and degradation ratio of plant fibres largely depend on the concentration of cellulose and lignin (a complex polymer), so a higher concentration naturally gives greater durability. Natural fibres are chosen for geotextiles production depending on their mechanical characteristic. Recent works demonstrate that both coir and jute fibres display extraordinary material properties and exhibit outstanding performance on soil stabilization applications. The properties and composition of several natural fibres are introduced in I.

Table I. Properties of natural Fibres

Type of Fibre	Cellulose (wt%)	Lignin (wt%)	Hemicellulose (wt%)	Density (g/cm ³)	Tensile Strength (MPa)	Moisture absorption (%)
Flax	71-78	2.2	18.6-20.6	1.4-1.5	345-1500	7
Hemp	57-77	3.7-13	14-22.4	1.48	550-900	8-9
Jute	45-71.5	12-26	13.6-21	1.3-1.46	393-800	307
Kenaf	31-37	15-19	21.5-23	1.2	295-930	12
Sisal	47-78	7-11	10-24	1.33-1.5	400-700	56-230
Cotton	85-90	0.7-1.6	5.7	1.21	287-597	890-1165
Coir	36-43	41-45	0.15-0.25	1.2	175-220	130-180

Typically, natural fibres are very porous and highly water-loving owing to structural hydrophilic groups. When exposed to moisture these fibres expand and this impairs the cell wall, which in turn helps to increase the risk of microbial degradation. Moreover, due to dust and other natural constituents surrounding the natural fibres, they are also highly susceptible to damage in interfacial bonding between the fibre and the surrounding matrix. As a result, many studies have been completed for these surface modification strategies to maximize this important fibre-matrix adhesion. Coconut coir in particular is considered a great composite filler as it has lots of good properties: it is mechanically robust, lightweight, highly resistant to both heat and saltwater, inexpensive and abundantly available. Notwithstanding these advantages, natural fibres inherently possess low durability, which limits their possible engineering uses.

To overcome this issue, a range of treatment methods have been proposed. A common strategy here involves combining a certain proportion of synthetic material with natural fibres by manufacturing composite materials that are highly effective for long-term durability. Direct chemical treatments and surface modifications are often used to make durable for durability or long service life applications to fortify such material. These interventions usually comprise alkali treatment, benzylation, stearic acid application, acetylation, TDI, permanganate, anhydride, peroxide, silane, plasma and isocyanate

treatments. For use in the treatment with natural antimicrobial agents, it is expected that coir reacts well since coir is a lignocellulosic fibre.

However, the current scientific literature on the effect of these natural antimicrobial treatments on coir is rather sparse. This research, therefore, aimed in particular to evaluate the impact of Cashew Nut shell Liquid (CNSL) on the microbial degradation of coir fibres. CNSL is an economically easy, environmentally sustainable means of treatment which completely negates the use of artificial resins.

1.4 COIR FIBRES

Coconut plantations grow on a diverse basis on Indian soils. Cultivation spans multiple regions, including Kerala, Tamil Nadu, Karnataka, Andhra Pradesh, Odisha, Goa, West Bengal, Puducherry, and Maharashtra, alongside the Lakshadweep and Andaman & Nicobar Islands. However, most of this crop is grown in the gravelly lateritic red clay soils of northern Kerala and the coastal regions of Karnataka. Coir, a lignocellulosic fibre, is directly extracted from the coconut's mesocarp. As a result of its good mechanical performance, low cost and ecological consideration, coir has appeared as the most widely practiced natural fibre geotextile. Its robust tensile strength effectively resists debris displacement and surface flow on steep topographies, while its superior durability allows vegetative establishment or stabilization of land in general. In addition, the environmental issue of non-biodegradable synthetic geotextiles also has driven up engineering interest in coir replacements. Coir has been shown to retain better strength levels with significantly higher intrinsic resistance to degradation than other natural fibres.

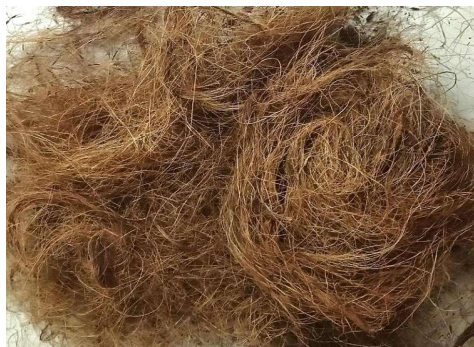


Figure 2: Coir Fibres

Natural fibres used many times in history, for they provide an eco-friendly property and are utilized almost everyone. Strategic deployment of natural materials, such as coconut coir, combine structural strength and elasticity in strategic manner. In countries like India, where resources such as these are locally abundant and financially acceptable, the use of coir for soil improvement is a sustainable and eco-friendly option of greatest possible value. With a much higher rate of lignin and lower cellulose content, coir is one of the most rigid natural fibres. This special mix will lead to it being the best—and most widely used—fibre types for tasks such as soil stabilisation, subgrade reinforcement and erosion control.

In addition to this, its high level of lignin significantly protects against degradation, resulting in a good, four-to-ten-year life of the fibre, much more robust than that of other products such as jute. Coir has a water absorption capacity of 130–180% and structural diameters between 0.1 and 0.6 mm. Mechanically, it showed a very good elongation ability, but with a significantly reduced initial tenacity, and it retains an important part of its tensile strength even when it is fully saturated.

Moreover, coir has higher friction coefficient than synthetic fibres, which accounts for better resistant nature and active suppression toward adjacent soil matrix swelling tendency. The precise biodegradation rate of coir is very dependent on the embedment medium and weather conditions; indeed, researchers reported coir retained up to 80% of tensile strength at 6 months post-encroachment in clay environment. Experimental studies also show that the total increase in water uptake of the soil composite due to a high percentage of incorporated coir is accompanied with the increase in tensile strength of the reinforced soil. Finally, the durability of these natural fibres can be further improved through targeted chemical processing or surface treatments with phenol, bitumen and specific polymers.

1.5 CASHEW NUT SHELL LIQUID (CNSL)

Cashew Nut shell Liquid (CNSL) is a highly valuable agricultural byproduct sourced from the cashew industry. Derived directly from the cashew tree, the nut boasts an approximately 1/8-inch-thick outer shell. Beneath this shell lies a delicate, cellular honeycomb structure containing a viscous, dark reddish-brown resinous liquid called CNSL. This natural extract inherently has potent antifungal and anti-termite properties. Moreover, owing to its remarkable mechanical flexibility, economic viability, and excellent solubility across the vast majority of common solvents, CNSL serves as an exceptionally versatile and ideal precursor material for the formulation of advanced surface coatings.



Figure 3: Cashew nut shell liquid (CNSL)

Although the lifespan of coir fibres is significantly longer than other natural alternatives, they are still critically questioned for their durability in a geotechnical context. Under normal environmental conditions (up to approximately three years), their natural degradation rate limits their functional lifetime. Coir exteriors feature several micro-pores and an irregular texture, which actively absorbs moisture from the surrounding soil matrix. Over time the moisture penetrates through the voids and causes volumetric expansion within the fibres. Under ambient conditions, the swelling of the cellular wall leads to degradation of the cell wall structure which creates favourable conditions for microbial growth that will cause microbial accumulation, progressively decreasing the strength of the fibre. As such, with increasing the strength and durability of coir geotextiles, surface treatments with conventional chemicals and minerals have been used to make them more stable, but these still lead to significant soil contamination.

Chemical agents embedded on the fibre surface are leaching into aquifers, endangering groundwater supplies. In addition, the leachates of these pollutants have the potential to significantly influence soil pH, generating environments that are very acidic or alkaline, ultimately affecting the native microbial populations negatively and depleting soil aeration processes.

Therefore, a fundamental engineering task is to engineer surface modification methods to increase fibre durability without adversely affecting the environment. In order to overcome the ecological problem, biopolymer-based surface modification is an environmentally friendly strategy. Recently, the academic literature emphasizes the use of Cashew Nut Shell Liquid (CNSL) as an effective, environmentally benign surface modifier. This CNSL is a dark brown, viscous resin that is extracted during the commercial processing of cashew nuts and is contained inside the fragile honeycomb composition of the nut's outer shell. In India it forms an exceptionally durable, renewable product of the cashew industry and is manufactured so prolifically that one-third of the nation's output is produced in India—including in the state of Karnataka. Characterized by high chemical resistance, CNSL is usually employed in thermosetting polymers strengthened with natural fibres.

CNSL, endowed with a combination of antimicrobial and acid-resistant activity, is widely used in industry, including polymer production, automobile and energy industries. Used as a treatment for fibre-reinforced soils, it acts as a natural disinfectant which effectively combats microbial degradation when applied to fibre-reinforced soils. After all, not only does this biopolymer coating extend the intrinsic durability of the coir material but also increases the mechanical strength of the coir composite due to increased interfacial bond that the reinforcing fibres form, as well as the interfacial bond between soil and soil.

1.6 MOTIVATION FOR THE STUDY

A pavement's lifespan is intrinsically connected to its subgrade soil; subgrade weakness can cause surface fractures to be formed. Thus, a new reinforcing material should serve to promote subgrade stability. Coir fibre, which has high lignin concentration, is also very strong and degrades more slowly than other natural fibres. Its initial mechanical and hydraulic properties—strength and stiffness, in particular—closely resemble synthetic polymer counterparts, while its advantage also includes the distinct advantage of extremely low raw material costs.

Nonetheless, its intrinsic biodegradability remains a primary constraint limiting its long-term application in civil engineering. To circumvent this and extend the functional lifespan of coir for prolonged geotechnical use, targeted chemical treatments and polymer coatings are utilized. Meanwhile, the development of natural fibre composites is advancing toward the creation of eco-friendly matrix materials that deliver superior performance at a lower cost than conventional synthetic matrices. Resins obtained from natural resources possess robust structural properties; their monomeric compounds can be cross-linked to formulate renewable, cost-effective, and environmentally sustainable polymer matrices. Cashew Nut Shell Liquid (CNSL) oil, a commercially viable phenolic-based monomer, serves as an outstanding natural resin precursor. Ultimately, the application of CNSL as a protective resin for natural fibre reinforcement has yielded highly promising results in recent studies.

1.7 OBJECTIVES

Aspects of this investigation are as follows:

- To evaluate the enhancement of sand strength when reinforced with 30 mm lengths of both untreated and CNSL-coated coir fibres at varying fibre concentrations.
- To investigate and compare the water absorption capacity of untreated versus CNSL-coated coir fibres.
- To analyze the compaction behavior of sand reinforced with 30 mm fibres, determining the influence of varying fibre contents and surface treatments.

- To systematically examine the overall structural behavior of the soil-fibre composite with varying fractions of both coated and uncoated coir fibres.
- To determine the optimal fibre parameters (ideal fibre content and treatment) to achieve the maximum increase in the strength of the reinforced soil.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Soil reinforcement is the application of various methods to improve the engineering properties and the mechanical performance of soils by incorporating the most favourable materials with preferred properties. For the project life cycle, the most effective adaptation to replace conventional synthetic fibres with natural fibres significantly reduces the source carbon emissions. The literature on the use of natural fibres for geotechnical engineering is wide in and a few key investigations are given below.

The study conducted by **K.K. Shanthi (2008)** examined the properties of the black cotton soil mixed with sisal fibre. According to the study, increasing the sisal fibre content decreased both the maximum dry density (MDD) and the optimum water content; conversely, increased CBR and unconfined compressive strength (UCS) as well.

Ramasubharao (2014) studied expansive soil mixed with randomly placed, 5 mm long coir fibres coated with kerosene (0%, 0.5%, 1% and 1.5%). Water absorption capacity (WAC) of the fibre was decreased by 32% due to the use of kerosene coating compared to raw coir. For achieving optimum coir content (OCC) of 1%, the coated fibre-reinforced soil showed about 2.5 magnitudes higher UCS in comparison to the unreinforced soil, and its splitting tensile strength was higher than that of the reinforced soil by 50%.

Singh and Mittal (2014) was carried out to investigate the effects of enriching coir fibre in clayey soil with different amounts of coir fibre (0.25%, 0.50%, 0.75%, and 1%). Sample preparations at MDD and OMC for UCS and wet and non-soaked CBR tests were done. The results showed that CBR values were consistent with fibre content; by adding 1% coir the soaked CBR increased from 4.75% to 9.22%, and the unsoaked CBR increased from 8.72% to 13.55%. At the same time UCS also increased from 2.75 kg/cm² to 6.33 kg/cm². The improvement not only results in reduced pavement thickness but also improves the behavior of the soil from being brittle to ductile that pays huge economic dividends for highway construction.

In another experiment, **Lekha (2014)** studied the stabilization of lateritic soil for low-volume roads with randomly distributed arecanut coir (~0.2% to 1%) reinforced with 3% cement by a binding material. Laboratory checks performed for UCS, CBR, durability, and fatigue behavior indicated significant increase of UCS and CBR values when using a composite of 1% coir fibre and 3% cement.

And, the effectiveness of CNSL protective coatings for coir yarns was experimentally validated by **Sumi (2017)**. Applying optimized concentrations of the solution to pre-treated yarns resulted in a 95% reduction of surface fungal growth. The study also detected higher hydrophobicity, significantly lower moisture absorption and tensile strength in the region of 17%, demonstrating that CNSL-treated fibres have potentially powerful applications in advanced geotextile design.

Lakshmi (2018) in his research sought to strengthen the mechanical properties of the locally clayey sand (SC). He used non-woven coconut coir fibre given randomly and at unequal concentrations (0.3 to 1.5%), ranging from 1 cm long to 5 cm in length. The 1.2% fibre content with lengths between 2 cm and 3 cm generated the largest gain, with 43.2% to 47.4% increase in UCS and a soaked CBR value around four times in excess of the unreinforced baseline.

Sivakumar Gowthaman et al. (2018) investigated soil reinforcement techniques based on natural plant fibres. At 0.8% the researchers determined that 10 mm jute fibres were able to do optimally in soft soils. Coir was reported to deteriorate quickly and lose

its properties in untreated conditions, but it showed the best properties at 0.6% addition. Sugarcane bagasse exhibited significant ability to stabilize relatively wide soil and was best at a 2% inclusion.

Prithviraj (2023) investigated the effect of CNSL on the coir geotextiles embedded in sand through direct shear tests. Experimental results indicate that geotextiles modified by CNSL significantly improved all interface shear strengths (including apparent cohesion, interface coefficient and interface friction angle) in all tested sand fractions, in addition to raising the tensile strength of the geotextile by 13%.

2.2 GAPS IN LITERATURE

A comprehensive review of the state of the art related to natural fibres, contributing to a holistic understanding of the behaviours of fibre-reinforced soils. Yet, the review also points to a noteworthy absence of investigation into interface behaviour of granular soils reinforced with biopolymer-treated coir. Studies conducted to date have mainly focused on tensile strength and long-term durability of the Cashew Nut shell Liquid (CNSL)-treated coir, at the expense of the geotechnical interaction between the CNSL and soil matrix. This oversight prompted the present systematic exploration of the specific effect of CNSL-treated coir fibres on sandy soils. As a result, a complete set of tests was designed to compare the soil changes induced by CNSL-processed coir versus those performed by untreated fibres. The literature is clear that there is a lack of empirical evidence for sand reinforced with CNSL-modified coir fibres. In order to overcome this issue, in this study, we conduct direct comparison between untreated and treated specimens.

Accordingly, the fundamental research limitations identified from the review are: No reports were available which have considered the water absorption and compaction behaviour of soils reinforced with untreated and CNSL-treated coir. The specific strength characteristics imparted to granular soils by CNSL-treated coir fibres have not also been studied. The limited comprehensive comparative comparison of untreated and CNSL-treated coir on the main geotechnical parameters (water absorption, compaction, strength)

is identified as a scarce problem. There is still no previous research which indicates the optimum fibre parameters (length and content) for an increased structural adaptation of a CNSL coating.

CHAPTER 3

METHODOLOGY

3.1 GENERAL

The adopted methodology of this study is briefly explained here.

3.2 METHODOLOGY ADOPTED IN THE PRESENT STUDY

Literature papers were studied on soil reinforced with coir Fibres of various soils. The following flow chart of the adopted methodology in this study is shown in Fig. 4.

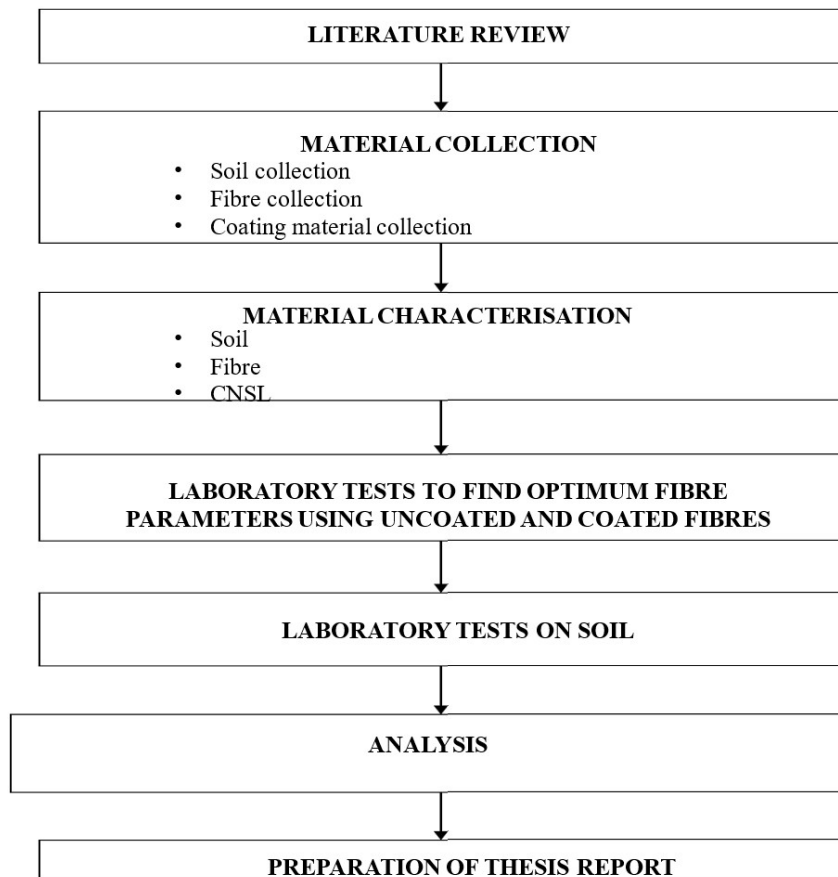


Figure 4: Flow chart of metrology

CHAPTER 4

EXPERIMENTAL PROGRAMME

4.1 GENERAL

This chapter articulates the materials selected in the study i.e soil, coir fibres, and Cashew Nut shell Liquid (CNSL), and their basic engineering properties. It also consists in detailing the detailed laboratory methodology implemented to systematically optimize conditions for untreated and CNSL treated coir fibres. For the longterm durability of the fibres, soil burial studies were conducted under strictly controlled environmental conditions to see how the coir fibres could react under changing conditions. This experimental setup was designed to simulate the most extreme conditions and worst-case field scenarios. In the long run, the progressive degradation rate of the coir was expressed as the tensile strength tests performed on the fibre samples before and immediately after the period of embedment.

4.2 MATERIAL PROPERTIES

4.2.1 Sand sample

The sand sample was collected from Mcd primary school, Paschim Vihar, which lies behind Sahibi Canal with geographical coordinates 28.665N, 77.122E as shown in fig. 5.

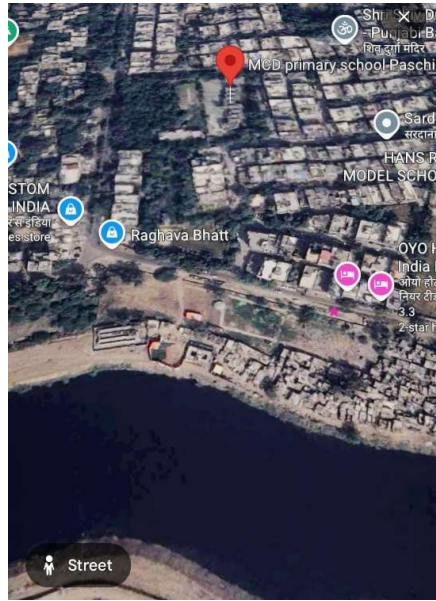


Figure 5: Soil collected site location

The sand sample collected from this site has natural moisture content (8.77%). The sample was air dried and index property tests were conducted according to the methodologies given in IS: 2720 (Part 5)-1985.

4.2.2 Grain Size Analysis:

The analysis of grain size is a basic technique used for assessing the size distribution of particles in soils, sediments, or aggregates. The determination of textural classification of the material through these tests is crucial to determine the key geotechnical characteristics (permeability, mechanical properties, and stability). This analysis is the primary goal of accurately describing the soil matrix as sand, silt, clay, or gravel. Thus this data allows interpretation of depositional environments, evaluation of specific drainage characteristics, and structural suitability for structural foundations. To systematically measure this distribution, a standard sieve analysis is made. This procedure involves passing the soil sample through a vertically arranged stack of sieves with progressively decreasing mesh apertures. The material retained on each individual sieve is then weighed to calculate from each separate size fraction its approximate mass percentage.

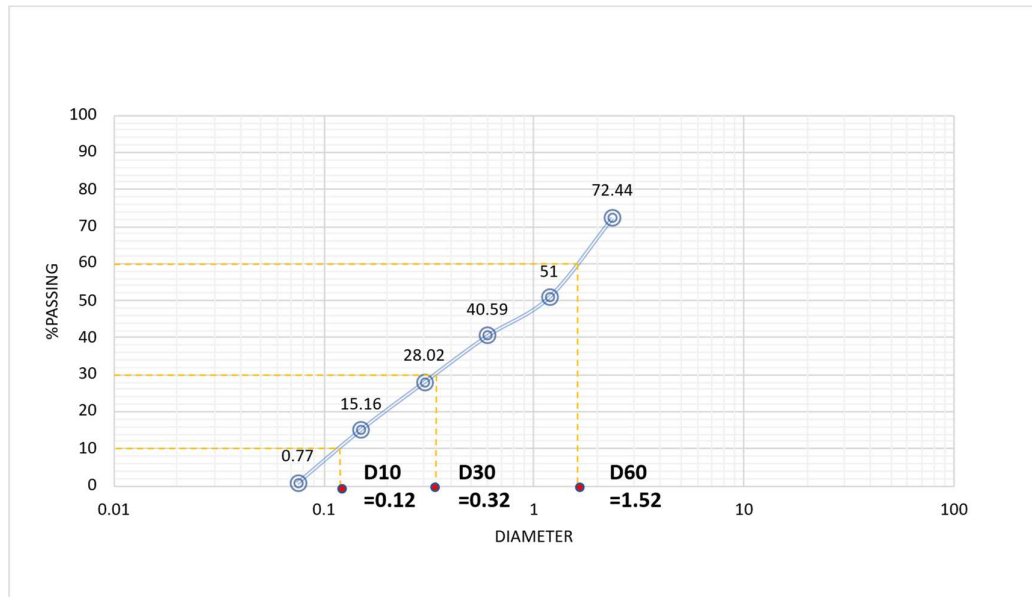


Figure 6: Grading characteristics of study soil

Parameters calculated are as:

Figure 6: Particle Size

- D_{10} (Effective size) : 10% finer particles, indicates drainage capacity.
- D_{30} : Particle size at 30% finer.
- D_{60} : Particle size at 60% finer, are used to calculate uniformity coefficient (C_u) and gradation coefficient (C_c).

From graph, we have found

$D_{60} = 1.52$ mm, $D_{30} = 0.32$ mm, $D_{10} = 0.12$ mm

- Coefficient of uniformity $C_u = 12.7$
- Gradation Coefficient $C_c = 0.56$

Since, $C_u > 6$ and C_c does not lie between 1 and 3, this sand is poorly graded (**SP**).

4.2.3 Atterberg Limits

4.2.3.1 Liquid Limit (WL)

The liquid limit is a fundamental property of fine-grained soils, controlling the critical water content when a material will change from plastic to liquid and begin to flow under its own weight. Its major goals are to establish consistency and mechanical behaviour of clayey soils, providing crucial data for estimation of the overall soil

strength as well as compressibility and potential settlement characteristics. The Casagrande apparatus is most commonly used in this kind of testing. The corresponding flow curve can be seen based on these laboratory observations.



Figure 7: Liquid Limit Apparatus

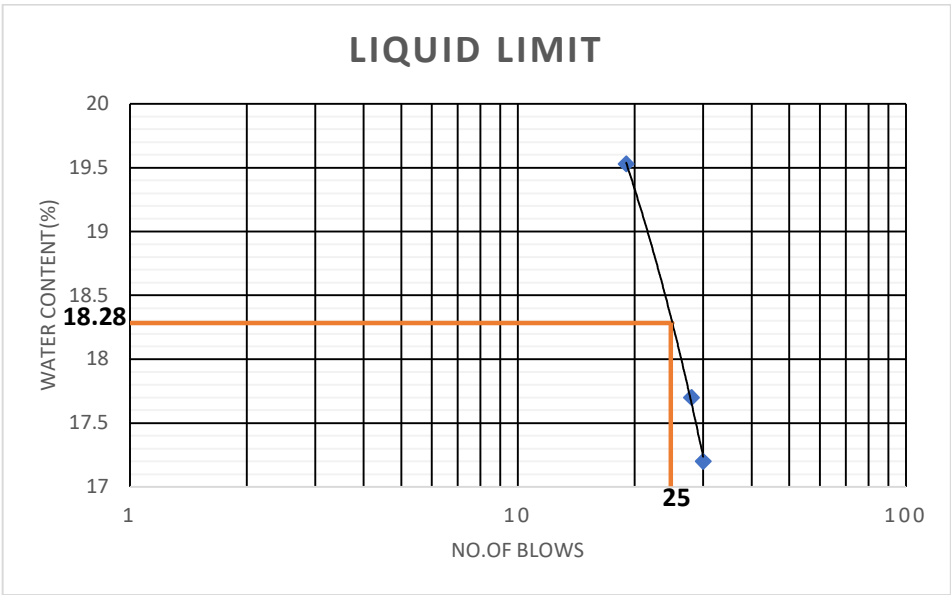


Figure 8: Liquid Limit Flow Curve

By Interpolation,
For 25 number of blows,
Water content = 18.28 %
 $\therefore$ Liquid Limit = 18.28 %

4.2.3.2 Plastic limit (W_p)

One of the definitions of the plastic limit is that where a soil enters a semisolid state, its moisture content is relatively critical. Thus, as a basic geotechnical characteristic, it denotes the minimum water content at which the soil specimen starts to crack and crumble when rolled into a continuous thread having a diameter of around 3 mm manually. Thus, the Plastic Limit was found to be 15.77%.



Figure 9: Plastic Limit

4.2.3.4 Plasticity Index (I_p):

The plasticity index (I_p) is defined as the range of moisture content at which a soil behaves plastically. The calculations are as followed:

$$I_p = LL - PL$$

$$I_p = W_L - W_p$$

$$= (18.283 - 15.77) \%$$

$$I_p = 2.513\%$$

4.2.4 Moisture Content Test

Moisture content is a percentage of dry mass expressed as an amount of water in a soil sample. It is an important parameter in soil mechanics, agriculture and materials science, with great impact on soil compaction properties, shear strength and mechanical behaviour. The properties of these can be quantified using several well-established methodologies such as the standard oven-drying method (conducted between 105°C and 110°C), calcium carbide method, torsion balances, electronic moisture meters. The natural moisture content of the soil considered in this study was 8.77% with the aid of an electronic moisture meter.

4.2.5 Specific gravity

The specific gravity of soil particles is defined as the ratio of the mass of soil solids to the mass of an equivalent volume of water. One of the necessary parameters for proper soil classification and essential information for determining some key geotechnical properties such as the void ratio and porosity. More importantly, specific gravity plays an important role in calculating the unit weight of soils in different environmental conditions and is important in modeling particle size distribution through wet analysis. Thus, to the tested soil samples, a standard pycnometer was employed to evaluate their specific gravity experimentally in this research. The Specific Gravity was determined to be 2.109.



Figure 10: Pycnometer

4.2.6 Standard Proctor Test

Soil compaction is the artificially induced mechanical process in which energy is exerted to restructure and compress the soil particles in a close manner. This operation effectively removes trapped air from the void spaces to reduce the total porosity — or void ratio — of the soil mass and to raise the dry density. The structural density of compacted soil depends on four essential factors including existing water content, the magnitude of the compactive effort applied, soil classification, and any chemical admixtures. As a result, the primary goal for a conventional laboratory compaction test is to calculate the exact moisture level needed in order to achieve the highest soil solids weight in a given unit volume of soil. This moisture threshold is formally described as the Optimum Moisture Content (OMC), and the maximum density experienced at this point is referred to as Maximum Dry Density (MDD).

Observations

- Diameter of the mould = 10.20 cm
- Height of the mould = 11.80 cm
- Volume of the mould = 964.21 cm³
- Empty weight of mould (W₁) = 4.184 kg
- Dry Density $\gamma_d = \gamma_b / (1 + W)$

Table II: Proctor test results

S.No.	Weight of mould (Kg), W_1	Weight of compacted soil + mould (Kg), W_2	Volume of mould (cm^3)	Water added (%), W	Bulk density (g/cc), γ_b	Dry density (g/cc), γ_d	Dry density (kN/m^3), γ_d
1	4.184	5.382	964.21	6	1.596	1.505	14.758
2	4.184	5.530	964.21	8	1.744	1.614	15.827
3	4.184	5.594	964.21	10	1.826	1.660	16.279
4	4.184	5.560	964.21	12	1.864	1.664	16.318
5	4.184	5.450	964.21	14	1.834	1.609	15.778

The curve of compaction for unreinforced sand showed optimum moisture content (OMC) and maximum dry density (MDD) as 11.18% and 16.357 kN/m^3 respectively. The results of compaction curve for unreinforced sand as shown in fig. 11.

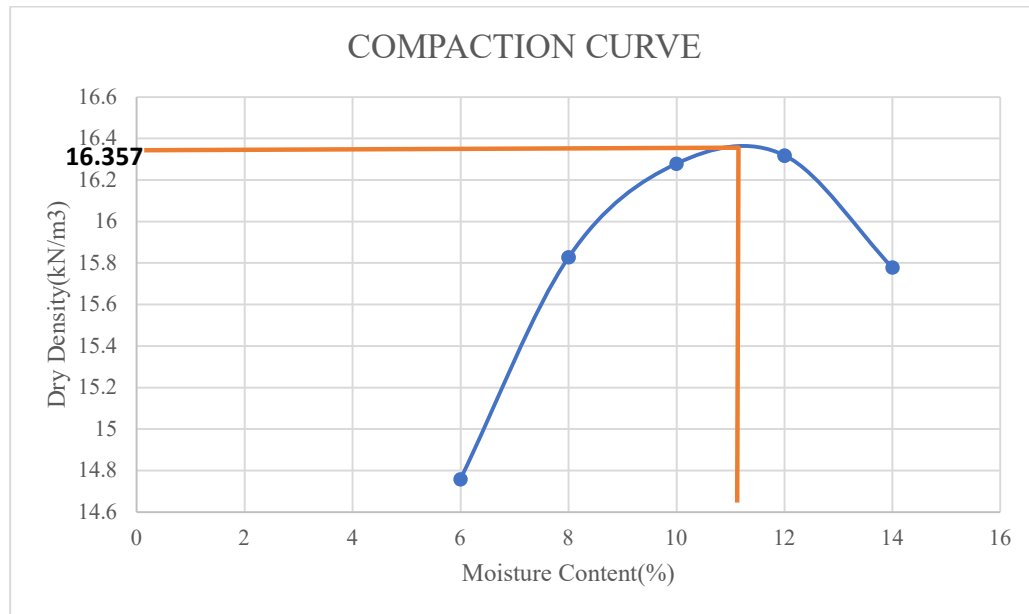


Figure 11: Compaction curve of unreinforced soil

4.2.7 Direct Shear Test

Direct shear testing is commonly conducted in geotechnical engineering to determine the stability of foundations, retaining walls, and slopes. It assesses lateral earth pressure to find the resistance of the soil to shearing forces, to measure the likelihood of slope failure, and to ensure that the soil has enough shear strength to support the bearing capacity. Cohesiveness (c) and angle of internal friction (ϕ) are two shear strength characteristics that can be found in a lab using the Direct Shear Test.

Calculations

The shear strength (τ) of soil is calculated using Coulomb's Law:

$$\tau = c + \sigma \tan \phi$$

Where,

τ = Shear strength

c = Cohesion (intercept on the y-axis)

σ = Normal stress

ϕ = Angle of internal friction (slope of the line)

Table III: Direct Shear Test

S.No.	Normal Stress(kPa)	Max. Shear Stress(kPa)
1	50	37.4602
2	100	72.1002
3	150	106.7402

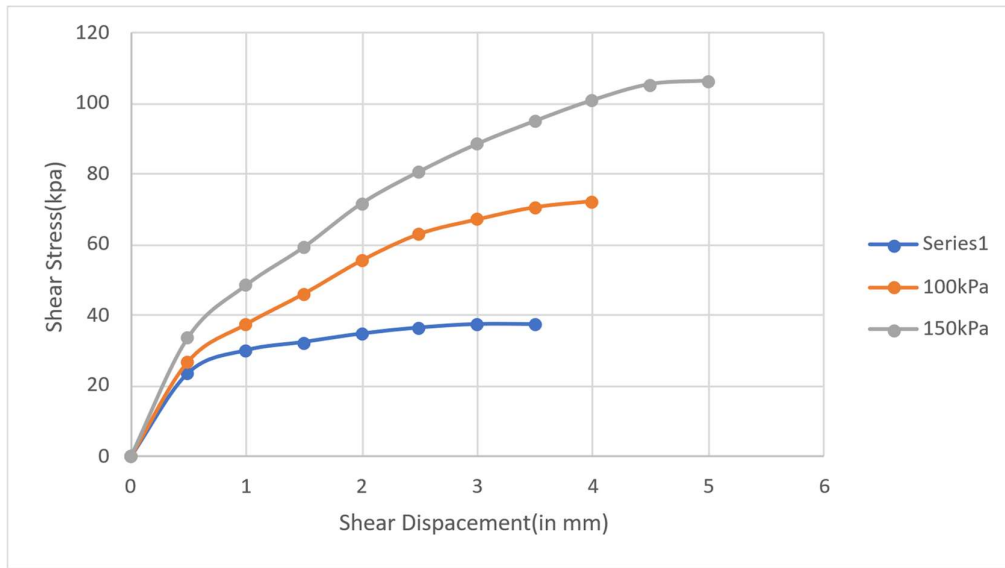


Figure 12: Displacement vs Shear Stress

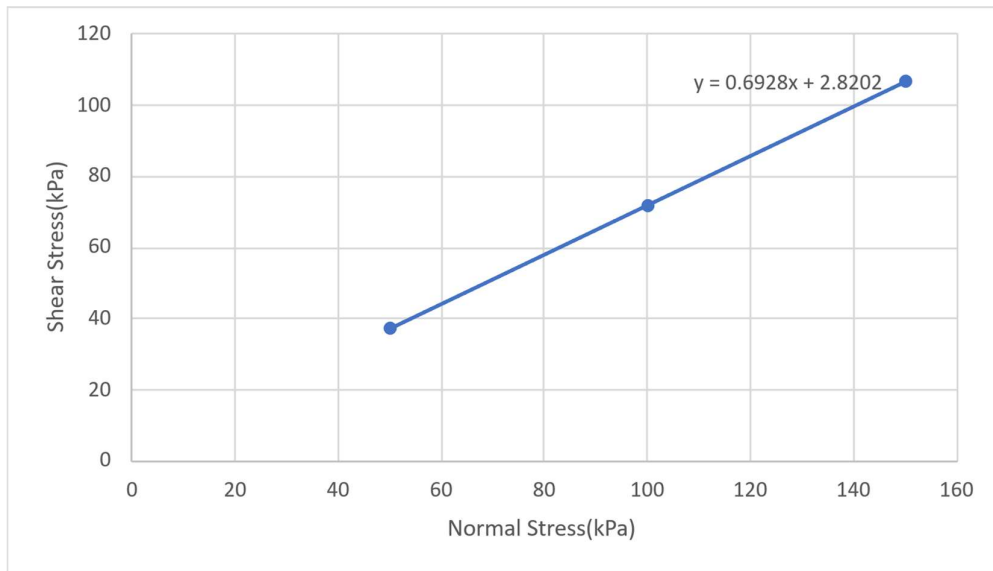


Figure 13: Normal Stress vs Shear Stress

From the above graph,

cohesion (c) = 2.8202 KN/m²

Angle of internal friction (ϕ) = 34.7°

4.2.8 California Bearing Ratio (CBR)

The California Bearing Ratio (CBR) test is a penetration assessment utilized to evaluate the mechanical strength of subgrade soils and base course materials in road construction. It quantifies a soil specimen's resistance to penetration by a standardized plunger under strictly regulated conditions. The results are expressed as a percentage, denoting the soil's penetration resistance relative to a benchmark of standard high-quality crushed stone. Parallely, increased CBR values represent higher soil strength and a higher load-bearing capacity. This empirical evaluation is extensively employed in flexible pavement design to ascertain the necessary thickness of individual structural layers. Furthermore, depending on specific project prerequisites, the procedure can be executed effectively in either controlled laboratory environments or in-situ field conditions.

Table IV: California Bearing Ratio Test

Penetration (mm)	Load (Kg)
0	0
0.5	37.66
1	65.36
1.5	85.22
2	95.35
2.5	103.59
3	109.65
3.5	117.54
4	125.3
4.5	130.63
5	135.643228
5.5	145.29

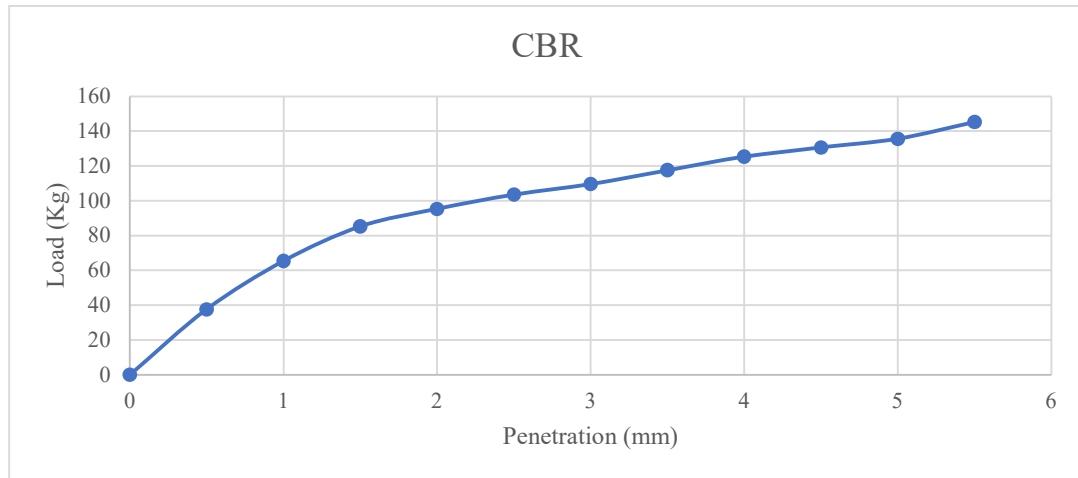


Figure 14: Penetration vs Load

From the above table, we obtain CBR at 2.5mm = 7.56%

And CBR at 5mm = 6.6%

Therefore, value of CBR at 2.5mm that is 103.59Kg is taken for consideration.

The summary of laboratory test results on the index properties of the sand is detailed in below table V.

Table V: Summary of index properties test

Laboratory test	Value
Specific gravity	2.109
Natural water content	8.44%
Grading	
Sand	99.23%
Silt and clay	0.765%
Consistency limits	
Liquid limit	18.283
Plastic limit	15.99%
Plasticity index	2.293%
IS Classification	SP

Compaction test	
Optimum moisture content	11.18%
Maximum dry density	16.357 kN/m ³
Shear strength	106.74 Kpa
CBR	7.56%

4.2.9 Coir Fibres

The processed coconut Fibres were taken from a weekly market. The coconut Fibres were individually cut into lengths of 30 mm. Diameter of the Fibres was determined using vernier callipers upon averaging three readings along the Fibre length. Water absorption test was conducted on treated coir Fibres. The Summary of Fibre properties of the coconut coir Fibres have been tabulated in below table.

Table VI: Summary of Fibre properties

Physical property	Value
Colour	Light brown
Diameter	0.1mm - 0.5mm
Specific gravity	1.382
Water absorption	156.3%
Fibre length Content Selected for the Study	30mm
Fibre Content Selected for the Study	0.1%, 0.2% and 0.3%

4.2.10 Cashew nut shell liquid (CNSL)

The CNSL used in the study was attained from Sakti bio-fertilizers located in the town of Dhenkanal, Odisha State, India. The specifications of the CNSL according to the I.S. are given in below table.

Table VII: Summary of CNSL properties

Physical property	Value
Colour	Dark reddish brown
Solid content	100 %
Viscosity (30 degree)	550
Specific Gravity at 30° C moisture % by weight	0.950-0.970
Loss in weight on heating	1
Ash % by weight	2
Iodine Value	1

4.3 Coating application

4.3.1 Pre-treatment

Coir Fibres, before coating with CNSL, a little alkaline solution was used to wash Fibres. Washed Fibres were rinsed in water with a pH of 7.0 ± 0.5 and dried. The drying process was then vacuumed. Dried Fibres samples were soaked in 1% (w/v) for 24 hours in a copper c



Figure 14: Pre-treatment of coir Fibres with CuSO_4

sulphate solution at room temperature ($30 \pm 2^\circ\text{C}$). During the experiment, Fibres to solution ratio of 1:30(g/mL) were kept. The pretreatment coir Fibres were dried in a 70°C oven until they reached a consistent weight.

4.3.2 Coating

Surface modifications were achieved by coating the coir fibres with Cashew Nut shell Liquid (CNSL). Following established literature protocols (Sumi, 2017), a specialized solution comprising CNSL, a kerosene solvent, and nitric acid (HNO_3 at 1% w/w of CNSL) acting as a polymerizing agent was formulated and applied to the pre-treated fibres. A 40% CNSL concentration was used throughout this experiment to ensure accurate investigation into the specifics of this specific aspect of action for interface behavior. The nitric acid acts in this mixture as a strong acid oxidizer, which provides exceptional water resistance to the treated material. Additionally, in practice copper sulphate-based preparation method for the preliminary pre-treatment was proved to extend the life span of the coconut fibre as long as four years. A comparison between untreated coir fibres and those treated with CNSL is visualized in Figure 15.



Figure 15: a) Untreated coir Fibres & b) CNSL-treated coir Fibres

CHAPTER 5

SAMPLE PREPARATION AND TESTING

5.1 GENERAL

The air-dried sand samples were blended manually and uniformly with 3 cm long coir fibres at varying percentages ranging from 0.1% to 0.3% by dry weight of the coir. Table V presents the analytical results derived from multiple experiments designed to evaluate the structural characteristics of the sand matrix when reinforced with randomly dispersed untreated and CNSL-treated coir fibres. To comprehensively assess these composites, the following primary laboratory evaluations were executed utilizing both fibre variants: (1) Water Absorption tests, (2) Standard Proctor compaction tests, and (3) Direct Shear tests.

5.2 WATER ABSORPTION TEST

Fig. 5.1 depicts the laboratory tests of water absorption experiments on coir treated and CNSL treated coir Fibres. Fibres were soaked in distilled water for 24 hours, drained for a duration of 10 minutes, and measured to the closest 0.01g. The ratio of the weight of water absorbed by the coir Fibre to the dry coir Fibres weight is used to calculate water absorptive capacity. This test is carried out for both untreated and CNSL-treated Fibres.



Figure 16: Water absorption test on a) Untreated coir Fibres & b) CNSL-treated coir Fibres

5.3 COMPACTION TEST

A standard Proctor compaction test was performed to evaluate the requisite compactive effort and moisture content for the soil specimens. This laboratory procedure determines the Optimum Moisture Content (OMC) at which a specific soil achieves its peak Maximum Dry Density (MDD). For this study, compaction assessments were executed on both unreinforced sand and soil mixed with untreated and treated coir fibres across various concentrations. First, 3000 g of air-dried sand was weighed, and coir fibres were prepared in 30 mm lengths. These fibres were then uniformly integrated into the dry soil in percentages of 0.1%-0.3% by dry weight. The soil-fibre matrix was manually blended with an initial 6% water content for a uniform distribution. The compaction was then continued with incremental 2% increases in moisture content. This systematic evaluation was performed on each concentration (0.1%, 0.2% and 0.3%) of the untreated and CNSL-treated fibres to determine the corresponding OMC and MDD values.



Figure 17: (a) 30mm coir reinforced soil (b) Compaction of coir fibres and dry soil

5.4 DIRECT SHEAR TEST

The Direct Shear Test of coir-reinforced sand was performed on a large-scale shear box. The sand was added in four equal granular subsoil layers into the direct shear box and the density was uniform. For the filled box, a loading block was set onto the granular soil mass and adhered firmly so that the load symmetry was maintained. For the reinforced specimens, the coir geotextile was placed at the interface of the lower shear box. On one longitudinal end of the lower box, the geotextile was securely adhered to a steel clamping block. For the initial sample preparation, upper and lower boxes were located with loading pins to measure their position (this was then removed prior to testing) to help improve relative lateral motion. The experimental program was carried out at three different normal stress levels: 50 kPa, 100 kPa, and 150 kPa. The shear displacement rate was maintained approximately 1.25 mm/min for all trials. From the above, the shear resistance for the composite was evaluated using a proving ring connected to the upper shear box and the lateral displacement was tracked using a dial gauge in the front of the assembly.



Figure 18: Direct Shear testing machine



Figure 19: Reinforced soil sample

This test is performed till concurrent results are obtained. The process is repeated with both untreated, and treated coir Fibres for other Fibre contents of percentages 0.1%, 0.2%, and 0.3%.

5.5 CALIFORNIA BEARING RATIO TEST

Laboratory 4-day unsoaked California Bearing Ratio (CBR) tests were carried out on lateritic soil samples using randomly distributed untreated and CNSL-treated 30 mm in length coir fibres. Five thousand g of dry soil was mixed with coir fibres at a concentration of 0.1% by dry weight of the soil in each specimen. To attain maximum dry density, the measured soil and fibres were continuously mixed at an optimum moisture content as determined. The resulting mixture was homogeneously compacted in 5 equal layers in a standard CBR mould, according to advice in IS 2720 (Part 16) – 1987.



Figure 20: CBR

The same procedure was applied for both the untreated and CNSL-treated fibres at the residual concentrations of 0.2% and 0.3% in a systematic manner. The penetration load values at depth 2.5 mm and 5.0 mm were obtained at the stage of the test. According to engineering recommendations, if CBR achieved at 2.5 mm penetration was higher than 5.0 mm penetration, this former value was chosen as design value. When a 5.0 mm penetration resulted in a higher CBR percentage, the test was repeated for confirmation.

CHAPTER 6

EXPERIMENTAL OBSERVATIONS, RESULTS AND DISCUSSIONS

6.1 GENERAL

Results from all the laboratory tests performed to analyse the water absorption capacity and strength improvement of sand reinforced with untreated and cashew nut shell liquid treated coir fibres are discussed in this chapter.

6.2 EFFECT OF UNTREATED AND CNSL-TREATED FIBRES ON THE WATER ABSORPTION CAPACITY

We used water absorption capacity tests to assess differences in moisture intake between untreated compared with CNSL-treated coir fibres. The high water absorption exhibited by untreated fibres was 138.5% according to experimental results. On the contrary, fibres treated with CNSL exhibited a markedly reduced capacity of 59.3%. This surface modification achieved a reduction in the moisture absorption potential of 57.2%. The CNSL treatment decreases the rate of biological degradation and of moisture-induced swelling, by making the fibre surface more hydrophobic. Hence, this lower water affinity results in the durability and service life of the coir fibres through robust resistance to microbial attack and environmental decay.

6.3 EFFECT OF UNTREATED AND CNSL-TREATED FIBRES ON COMPACTION CURVES

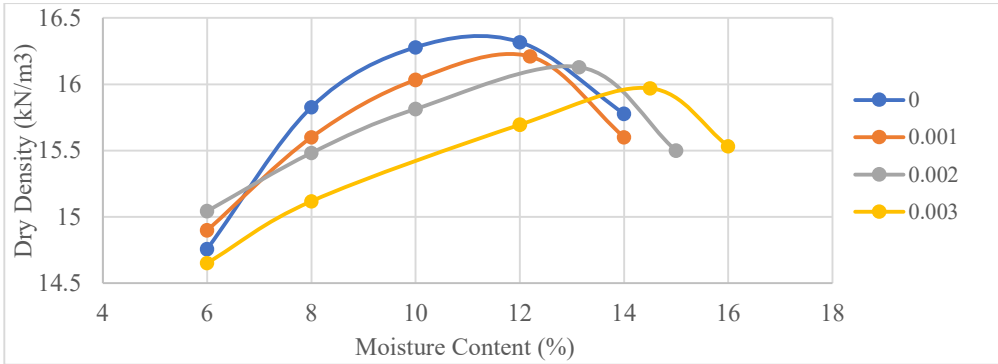


Figure 21: Compaction curves for 30 mm coir Fibre length (Untreated)

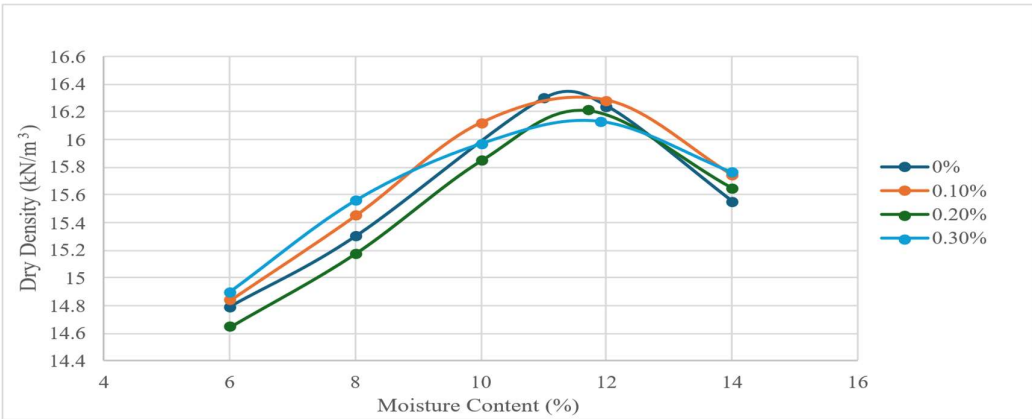


Figure 22: Compaction curves for 30 mm coir Fibre length (Treated with CNSL)

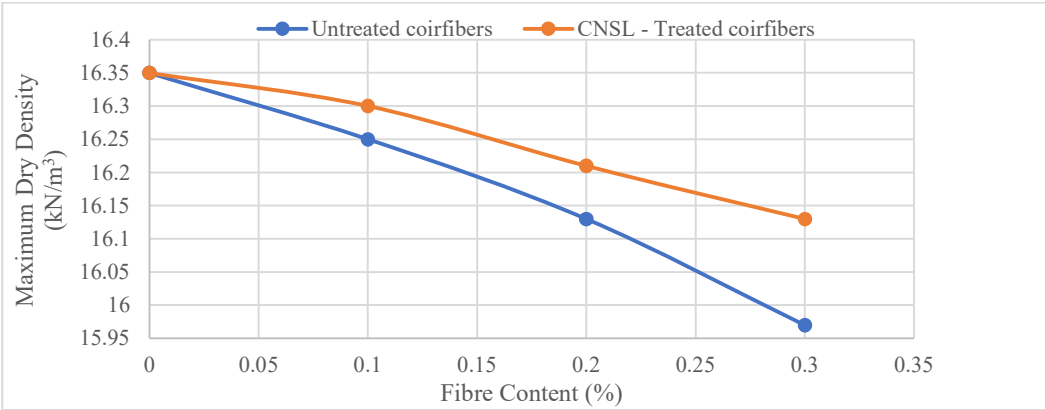


Figure 23: Effect of fibre content on MDD

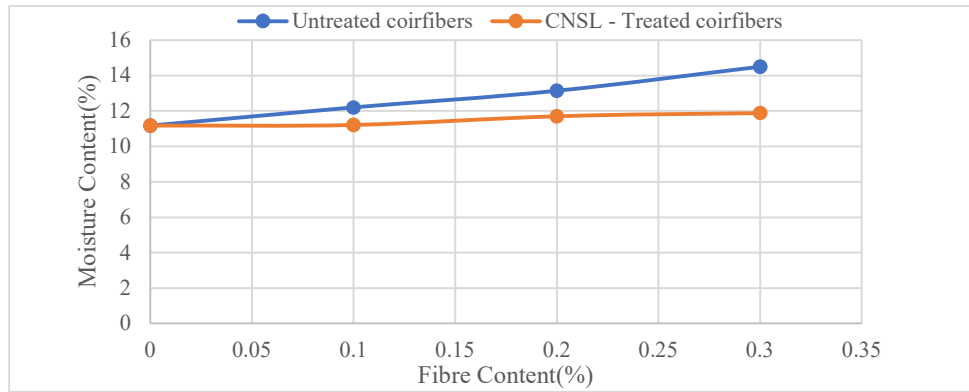


Figure 24: Effect of Fibre content on OMC

By comparison, the compaction curves illustrated in Figure 24 show that 30 mm untreated coir fibres show an overall greater moisture content than those treated with CNSL and present at varying concentrations. Each of the corresponding properties in OMC and MDD for each fibre type is presented in Table VIII. Compaction curves show that when fibre contents rise from 0.1% to 0.3%, OMC progressively increases, while the MDD decreases for both untreated and CNSL-treated specimens.

Although an upward trend in OMC was found in both examples, the increase is faster for untreated fibres compared to those treated with CNSL. This can be attributed in part to the fact that different water absorption capacities of the materials are the main cause of these results: untreated coir fibres had 138.5% water absorption capacity significantly greater than the 59.3% in the CNSL-treated fibres. As a result, the high hygroscopic property of untreated fibres requires a larger volume of water to achieve good compaction condition.

Table VIII: Laboratory results of compaction test results

Fibre content (%)	30 mm coir Fibre length			
	Untreated Fibres		CNSL-treated Fibres	
	MDD (kN/m³)	OMC (%)	MDD (kN/m³)	OMC (%)
0	16.35	11.18	16.35	11.18
0.1	16.21	12.2	16.45	11.21
0.2	16.13	13.14	16.30	11.53
0.3	15.97	14.5	16.13	11.89

Figure 22 MDD gradually decreases as the content of the fibres is increased, for both untreated and CNSL-treated coir (COIR) fibres. This MDD decrease is mainly due to the displacement of heavier soil grains by the much lighter fibre material as the reinforcement ratio increases. At higher concentrations, the fibres tend to form a flocculated internal structure, increasing the overall void ratio and ultimately reducing the MDD of the composite.

Figure 23 also emphasizes a decrease in MDD following CNSL treatment for fibre specimens. These conclusions are consistent with previous research which has reported, among other things, that inclusion of fibre results in a reduction in MDD and an increase in OMC along with it as reported by Lawer (2021) and Lekha (2015).

6.4 EFFECT OF UNTREATED AND CNSL-TREATED FIBRES ON STRENGTH CHARACTERISTICS

6.4.1 Direct Shear Test on Coir Reinforced Sand

Shear stress versus displacement behaviour for reinforced soil specimens is shown in Figure 25. The results indicate that all the coir geotextile-reinforced soil samples

had a higher shear strength than the unreinforced controls. At the normal stress of 150 kPa, shear strengths for 0.1%, 0.2% and 0.3% coir concentrations were significantly greater (110.332 kPa, 117.99 kPa and 113 kPa).

The failure envelope was determined following the Mohr–Coulomb criterion. As determined by Figure 25, little cohesion of the interface resulted, which indicates that the shear strength is mainly frictional. The interaction between the coir geotextile surface and individual soil particles, followed by the mechanical interlock, is the principal influence for the formation of these interfacial shear strengths that leads to this interface shear strength. The correlation between the highest interface shear strength and coir fibre content can be found in Figure 26 and 0.2% coir reinforced sand obtained the highest shear stress under all normal stresses applied were presented.

Previous studies by Sayida et al. (2020) points out that the composition of the local earth affects the degradation of coir geotextiles and hence the tensile strength. Accordingly, thorough durability assessments of untreated and treated coir geotextiles in a robust manner continue to be important aspects of relevance for future research.

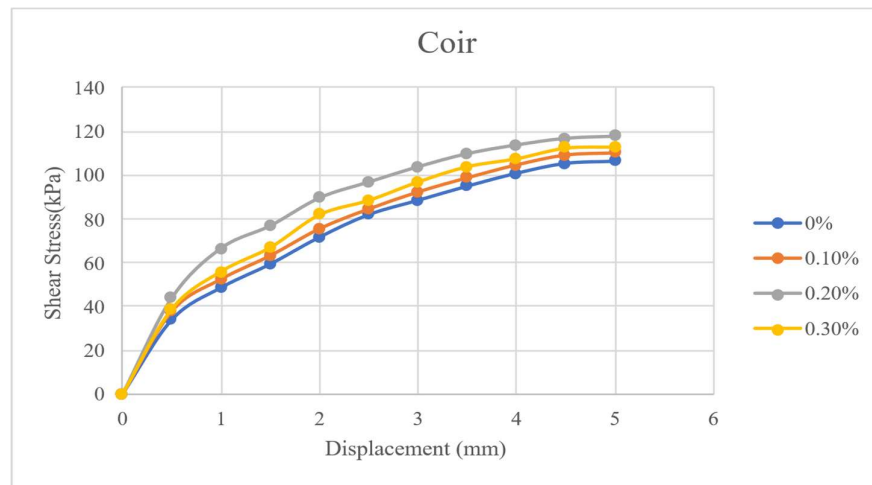


Figure 25: Results of DST

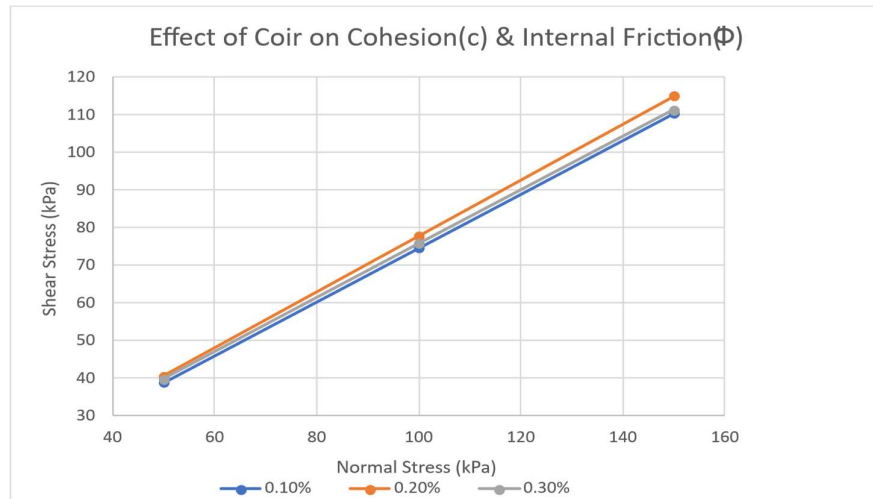


Figure 26: Effect of Coir on Cohesion & Internal Friction

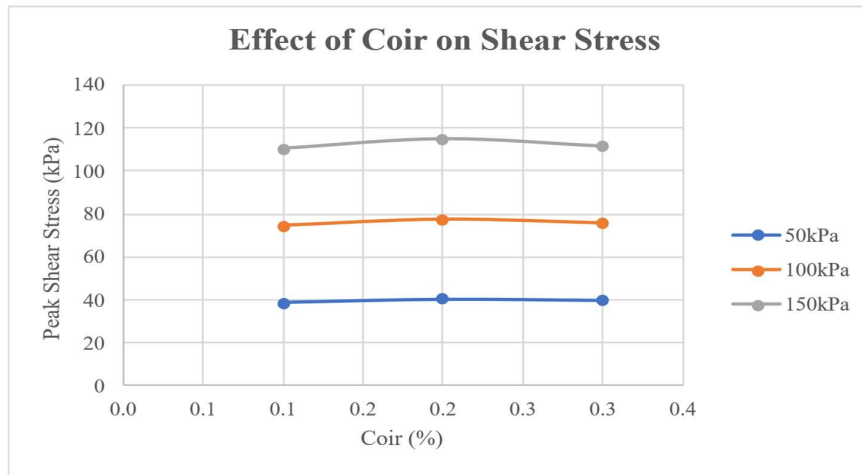


Figure 27: Effect of Coir on Shear Stress

6.4.1.1 Direct Shear Test on CNSL treated Coir Reinforced Sand

Figure 27 shows the shear stress versus displacement response in sand reinforced with CNSL-treated coir geotextile. The peak shear stress values recorded for 0.1%, 0.2%, and 0.3% fibre concentrations tested at the normal stress of 150 kPa were 116.011 kPa, 117.4 kPa, and 116.41 kPa. The surface modification of the coir geotextile with CNSL is shown in Figure 28 with both peak shear strength and internal friction angle increasing at the same time. We note that the improvement is due to the CNSL coating which covers up the surface pores of the fibres effectively and increases the effective contact area between soil particles and reinforcement.

The results correlate with the findings of Vivek, Dutta, and Raman (2018) which stated that surface treatments significantly reduce voids on geotextile surfaces. As it can be seen, experiment shows that soil reinforced with coir fibres has also increased values of cohesion (c) and friction angle (ϕ). The unreinforced soil had an initial cohesion of 2.8202 kPa and internal friction angle of 34.7° . Following reinforcement with CNSL-treated coir fibres, the cohesion value experienced a substantial increase, peaking at 4.6 kPa for the 0.2% fibre content specimen—a total percentage increase of 63.10%.

Furthermore, the friction angle demonstrated a consistent upward trend relative to the concentration of fibres integrated into the soil matrix. With the application of CNSL treatment, the friction angle for the 0.2% fibre content increased from the baseline 34.7° to 36.94° . The maximum friction angle was achieved at a fibre concentration of 0.3%, reaching 36.99° , which represents an overall enhancement of 6.59% compared to the unreinforced state.

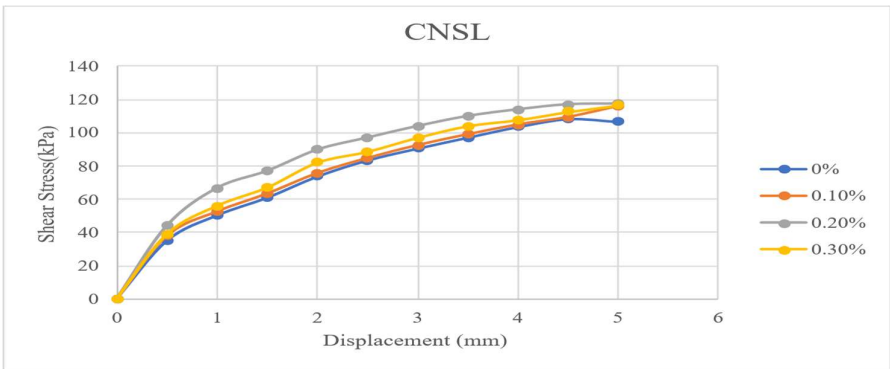


Figure 28: Results of DST on CNSL Treated Coir

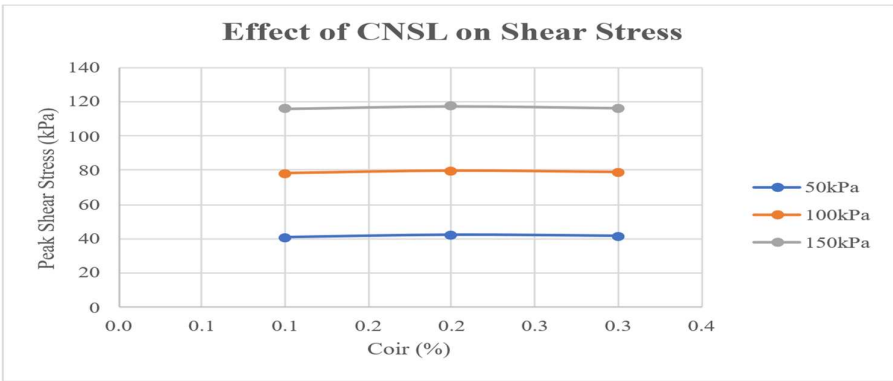


Figure 29: Effect of CNSL on Shear Stress

Table IX: Effect of CNSL on Shear stress

Normal Stress (kPa)	Unreinforced (kPa)	Shear Stress for 0.1% Coir (kPa)		Shear Stress for 0.2% Coir (kPa)		Shear Stress for 0.3% Coir (kPa)	
		Coir	CNSL	Coir	CNSL	Coir	CNSL
50	37.4602	38.74	40.66	40.49	42.2	39.84	41.51
100	72.1002	74.5362	78.336	77.74	79.8	75.77	78.96
150	106.74	110.332	116.011	114.99	117.4	111.37	116.41

Table X: Cohesion and Internal frictional angle

	Untreated Coir		Treated Coir	
	C	Φ	C	Φ
0.10%	2.9441	35.59	2.98	36.83
0.20%	3.24	35.57	4.6	36.74
0.30%	4.13	36.68	4.06	36.79

6.4.2 California bearing ratio (CBR)

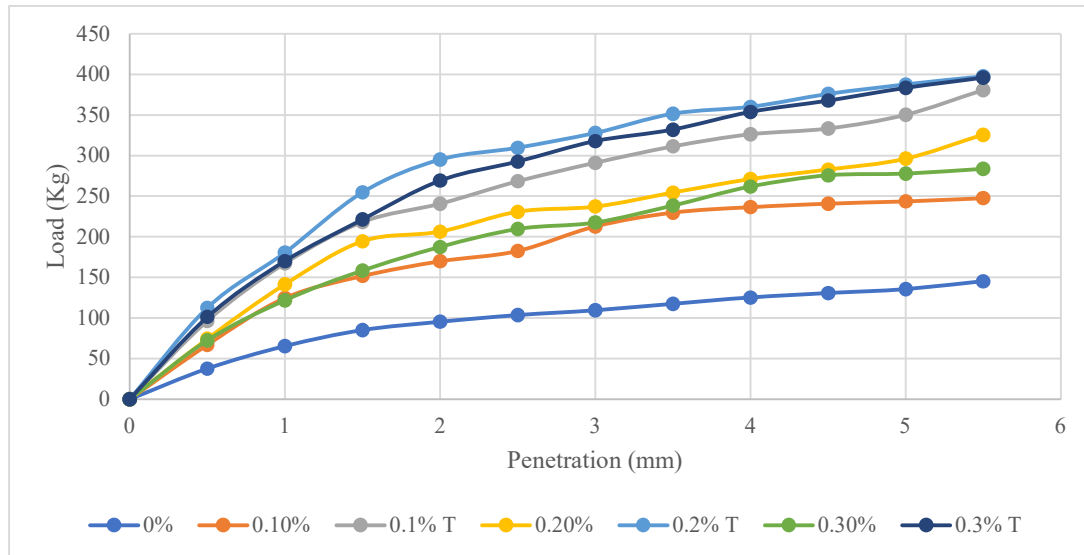


Figure 29: Load Displacement Curves of CBR

Fig. 29 depicts typical load-penetration curves for unsoaked CBR with untreated and CNSL treated coir fibres of 30 mm in diameter. CBR strength rises with fibre content up to optimum content and then decreases because of the formation of flocs by fibres in soil mass in both untreated and CNSL-treated coir fibres. The peak values of CBR were found at a fibre content of 0.2%. The strength increase in untreated fibres is due to the increased mechanical interlocking between fibres and soil interface. The strength increase in CNSL-treated fibres is due to interface friction angle and tensile strength is enhanced as a result of CNSL surface modification of coir geotextile. Table XI depicts the unsoaked CBR values of untreated and CNSL-treated coir fibres in percentages.

Table XI: Laboratory Results of CBR test.

Fibre Content	Untreated (%)	Treated (%)
0	7.56	7.56
0.1	13.46	19.36
0.2	16.36	22.60
0.3	15.29	21.35

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 SUMMARY

This study investigated the application of randomly distributed natural fibres as a potential reinforcement for poorly graded sandy soil, specifically for use in low-volume village roads. The research focused on comparing the mechanical effects of incorporating untreated versus CNSL-treated coconut coir fibres on the subgrade characteristics. Sands have limited strength and are vulnerable to moisture variations, which adds to the engineering challenges. Nevertheless, coconut coir fibres are extremely attractive as geotechnical materials due to their high tensile strength and their biodegradability. Fibres were treated with Cashew Nut Shell Liquid (CNSL) to improve their durability and to enhance their compatibility with the sand matrix in this investigation. The comparisons were conducted to determine the effects of untreated and CNSL-treated fibres on water absorption, compaction and strength properties.

Experimental studies showed that the water absorption capacity of untreated coir fibres was much greater as compared to that of CNSL-treated fibres. Standard Proctor compaction investigations showed an increase in OMC and a decrease in MDD with the increase in fibre concentration. Significantly greater changes were observed in untreated fibres than those treated with CNSL. The increased OMC is linked to the hygroscopic properties of the fibres, whereas the decreased MDD is due to the displacement of heavier sand particles by the light fibre material. Direct Shear results indicated that CNSL-treated fibres produced higher peak strength. With 0.2% fibre, the untreated fibres exhibited an

increase of 1.07-fold in shear stress, whilst CNSL treated fibres demonstrated a 1.09-fold increase than the unreinforced soil. Additionally, California Bearing Ratio (CBR) test indicated maximum values at a fibre concentration of 0.2%. The resulting enhancement mainly results from the elevated interface friction angle and tensile strength of fibres provided by the CNSL surface alteration.

7.2 CONCLUSIONS

Herein, this research explored the effects of surface alteration on coir fibres by reinforcing poorly graded sandy soil by using CNSL in an attempt to give better reinforcement of ungraded sandy soil. According to the experimental findings, the following conclusion can be concluded:

- Hydrophobic improvement of the coir fibres; the moisture resistance of the coir fibres underwent enhancement with CNSL treatment, showing a 57.2% improvement in water insulating capacity, and their water absorption capacity decreased significantly. This is as the CNSL resin sealing the surface micropores is responsible for the barrier, thus preventing water from breaking into the micropores of the surface very early.
- Compaction properties of fibre: fibres allowed OMC to rise for all the two fibre types. Nonetheless, the rate of the OMC increase as compared to non-fibres was much higher, as this was predominantly as a result of their higher (hygroscopic) affinity.
- Density Trends: MDD for both untreated and CNSL treated specimens decreased continuously with higher fibre content as soil solids were substituted with lighter (fibre) content.
- Optimal Reinforcement Ratio : Shear-stress peak values of untreated soil and CNSL-treated fibre reinforcement soil reached at an optimal coir fibre concentration of 0.2%.
- Shear strength: In the 0.2% ideal fibre content, untreated fibres gave 1.07-fold higher shear stress and CNSL -fibre improved it more dramatically by 1.09-fold in comparison to unreinforced soil.

- Frictional Resistance: The internal friction angle of the soil matrix was remarkably increased. The addition of the shear resistance through the mobilization of fibres' tensile strength and better interlocking with the soil grains provides this improvement.
- The CBR after CNSL treatment was significantly greater than the CBR of untreated fibres. Untreated fibres at 0.2% fibre resulted in a 2.16-fold increase in CBR compared to 2.98-fold increase in CBR with CNSL-treated fibres over the base soil.

In conclusion, modification of the surface by CNSL, not only prevents the degradation due to moisture, but also supports the mechanical performance and durability of the coir fibres. Therefore, as an end result of treatment, it results in a better composite material resulting considerably to a greater structural stability and load-bearing capacity of sandy subgrades.

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