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ORIGINAL RESEARCH

An experimental investigation on the effect of vetiver grass root system on the engineering properties of soil

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Abstract

The research described in this paper centered on exploring the potential of vetiver plant roots for reinforcing slopes and mitigating erosion. Vetiver roots act as a natural defense against erosion by shielding the soil from raindrop impact and securely anchoring the root system. A laboratory study was conducted to investigate whether hybrid vetiver roots could enhance slope stability and mechanically reinforce the soil. A shear strength test was conducted with fiber concentrations of 0 to 2% in 0.5% increments and fiber lengths adjusted between 20 and 25 mm in this study. In conclusion, the presence of vetiver roots significantly increased the soil's shear strength. Silty clay soils were significantly affected by soil cohesiveness, especially in terms of shear strength. The study showed that adding vetiver roots to soil significantly improved the soil's shear strength parameters (c) and optimal moisture content (OMC), while lowering maximum dry density and raising OMC slightly. In addition, root fibers were added in order to improve the California Bearing Ratio (CBR). The study also found that soil treated with vetiver root fibers had much lower discharge and permeability constants. Specifically, the permeability constant and discharge dropped by about six times in marginal soil treated with 1% vetiver root fibers. The enhanced soil properties resulting from vetiver root reinforcement suggest that reinforced soil can be effectively utilized for slope stabilization. This insight can be instrumental in leveraging plants as a natural means of erosion control and slope stabilization, providing technical justifications for their application in such contexts.

Keywords Root · DST · Soil stabilization · Unconfined compressive strength · Permeability

Abbreviations

CI	Clay with intermediate plasticity
M	Montmorillonite
IS	Indian Standard
CV	Clay with very high plasticity
MH	Silt with high plasticity
CH	Clay with high plasticity
MV	Silt with very high plasticity
MDD	Maximum dry density
SEM	Scanning electron microscope
OMC	Optimum Moisture Content
DST	Direct shear test

Notations

RIF	Root induced fibre
Φ	Angle of internal friction
ZAV	Zero air void
SI	Shrinkage index (= LL − SL) (%)
PI	Plasticity index
PL	Plastic limit
C	Cohesion
PL	Plastic limit (%)

1 Introduction

The stability of natural slopes poses a universal challenge for civil engineers worldwide. Unlike man-made slopes such as dams and embankments, where engineers have some control over the materials used, natural slopes are governed by natural soil composition, offering limited control. Man-made slopes are categorized as finite slopes, as their failure plane intersects the sloping ground, whereas natural slopes are termed infinite slopes, as their failure plane runs parallel to the sloping. Numerous prior studies have endeavored measurement of changes in soil shear strength parameters caused by grass roots. For instance, Tengbeh (1993) conducted experiments with It was found that grass roots increased the shear strength of clay and sandy clay loam by 500%.

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Mickovski et al. (2005) performed direct shear tests in the field on Vetiver grass grown on a marl (lime-rich mudstone) terrace. The samples were prepared using the profiled wall method in conjunction with block excavation. The researchers observed a significant 36% increase in peak shear stress compared to equivalent tests conducted in a controlled laboratory setting. They also made note of the fact that soil containing roots displayed greater ductility and could endure higher displacement before yielding. However, it is regrettable that the specific data regarding the increase in shear strength parameters were not disclosed in their findings.

Gray and Sotir (1996) demonstrated that the hydraulic behavior of root-reinforced soil is influenced by both root growth and decay. As roots decay, the concentration and reinforcement provided by the roots decrease. This implies that proper maintenance is essential for bio-engineered slopes to remain stable over time, as the stability may diminish when plants wither and roots decay. However, there hasn't been a specific method proposed to quantitatively assess the impact of this phenomenon on slope stability. Furthermore, most previous researches have inadequately addressed the effects of suction and changes in root concentration over time on root reinforcement. These factors, despite being crucial to the overall stability of the system, have been scarcely considered in existing studies. A changing climate coupled with increased natural disasters, such as floods, landslides, means that effective and economical methods for reducing soil mass movement must be found. Plants root can reinforce soil and reduce the risk of landslides as well as erosion on natural and man-made slopes (Gray and Leiser 1982; Danjon et al. 2008; Baets et al. 2008; Ghestem et al. 2011).

It is essential to understand soil characteristics and properties before any construction work is done. This knowledge is important for determining the soil's load-bearing capacity and how it will respond to changes in external forces. Good soil engineering practices can help minimize the risk of landslides (Gobinath et al. 2020). Mediterranean environments face a serious soil erosion problem due to their dry, bare soil, which is very susceptible to erosion during rainstorms. As a result, there significant soil erosion occurring on-site, coupled with off-site impacts like sediment buildup in river channels or reservoirs and floods (Ali and Osman 2008). In order to prevent soil erosion along slopes, plants have been used for centuries. It has been shown that their roots reinforce the soil, improving its stability. In some studies, root systems have been found to enhance slope stability (Habibah et al. 2014). The roots of this grass are sufficiently long to nail the soil surface to prevent erosion. The extensive root system of vetiver can reduce erosion as a result of its ability to reduce erosive forces. It has been shown that vetiver can withstand a broad range of soil and ground water conditions. It can stop soil erosion with its base tillers. The open literature contains little published research on assessing the geotechnical characteristics of soils reinforced with plant roots. In order to assess the strength and permeability of a soil affected by a landslide, the roots of vetiver grass, a plant that grows readily in the area, are employed to fortify the soil.

The purpose of this study is to look at how soil shear strength is affected by soil reinforcement using grass roots. The unreinforced and grass-rooted reinforced soil types were evaluated. The parameters of soil shear strength may be improved by adding plant root reinforcement (Nareeman and Fattah 2012). The results of this study may have important ramifications for a number of applications, including construction projects in regions vulnerable to soil instability, erosion management, and slope stabilization. Knowing how well plant roots reinforce soil offers important information on sustainable and environmentally friendly ways to improve soil stability and avoid soil failure. It is clear from the body of research that grass roots affect the parameters of shear strength. Nonetheless, there is disagreement about the best modeling strategy because of how complex the different affecting components are. Thus, it was decided to use an empirical approach to quantify the impact of grass roots on shear strength parameters in silty clay soils.

2 Research significance

This study's primary goal is to look at soil bioengineering techniques for landslide prevention and slope stabilization in different roadside environments. The goal of the study is to investigate the viability and efficiency of using bioengineering techniques to manage erosion and stabilize soil slopes. It is anticipated that by the time the study concludes, workable bioengineering methods for landslide reduction and soil slope stabilization will have been identified and suggested.

3 Root morphology and strength

Through the utilization of these methodologies, researchers and engineers can methodically assess the contribution of plant roots to soil reinforcement and the improvement of slope stability. This thorough approach guarantees a reliable evaluation of both plant roots and the specific soil and site conditions, thereby resulting in more efficient and sustainable strategies for slope stabilization.

3.1 Root architecture

Structure Classification and Terminology: The vertical support root is a taproot located directly beneath the tree's trunk. Sinker roots are horizontal roots that extend from the central trunk and grow horizontally. Conversely, lateral roots are roots that emerge from the trunk but also grow horizontally. This characteristic has been documented in various tree species (Böhm 1979). As observed, the term "taproot" denotes the primary vertical root of a plant. "Sinker root" describes vertical roots that originate from the trunk or lateral roots beneath the tree's trunk, while "lateral root" refers to roots that emerge from the trunk or its laterals. Soil bioengineering techniques provide sufficient stability for the establishment of native vegetation and neighboring plants, allowing them to gradually assume this function. It is essential to comprehend the factors affecting the mass and surface stability of slopes to effectively implement soil bioengineering stabilization methods. This was highlighted by Pallardy (2007). Knowledge of slope vegetation's hydraulic and mechanical impacts is also essential if living plants and embedded plant pieces are used as soil reinforcements and drains. Hills and uplands are formed when tectonic forces bend the earth's crust. Mountain ranges like the Sierra Nevada can be formed when plutonic rock masses push up through the crust. On the other hand, the dual processes of surficial erosion and mass movement degrade and deteriorate these mountainous terrains and uplands. Cuts and embankment slopes, for example, are subject to the same deterioration processes as natural slopes. To regulate or prevent the wearing or withering away of the earth's surface, one must first comprehend these two degradation processes and the elements that influence them. While there are numerous similarities between the two processes, they also have significant differences. The separation and erosion of the surface layer classified as Taproot, heart root, and plate root shapes have been identified schematically in the diagram. Variations of these fundamental shapes are possible. Both genetics and environmental factors influence morphology. How a given root design develops in response to either of these causes determines the amount of contribution it makes to the stability of a slope with regard to the influence of seasonal effects is reported by Watson et al. (1999). Root systems with deep roots that penetrate likely to shear surfaces, such as vertical or sinker roots, are more likely to enhance stability against shallow sliding, improving a root-permeated soil mass's shear strength. In summary, root architecture plays a critical role in providing stability to slopes and preventing erosion. Understanding the types and functions of different roots helps in implementing effective soil bioengineering procedures to enhance slope stability and protect natural terrains.

3.2 Materials and methods

Figure 1a illustrates samples collected from a site affected by a landslide on the Mughal route in Shopian district, Jammu and Kashmir India. This route historically served as a vital connection between Kashmir's valley and the rest of India during the Mughal Empire. The samples were used to conduct various tests. To prevent the loss of moisture after soil samples were collected, some of them were bagged in waterproof plastic bags. Figure 1b–d shows that’s test performed in the laboratory. In order to prevent the mingling within the soil, amidst the roots of grass and plants, soil samples that were Soil samples were collected both from disturbed and undisturbed areas, each taken from a depth of 1 m below the ground's surface, ensuring the samples were structurally sound by taking great care when collecting metal cores. To preserve the natural moisture of the soil, wrapping the cores in plastic bags was done. An IS standard sieve of 2 mm was used to sieve the soil after air-drying, crushing, and sieving. The main categorization of soil samples was done using IS criteria. The particle size distribution curve is shown in Fig. 2.

3.3 Plant root collection

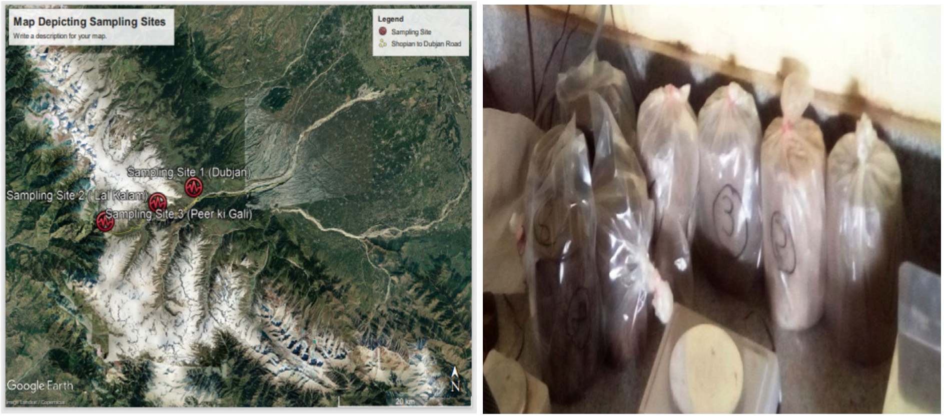
This study investigates the roots of various plants found in the Mughal Road area near Poshana, Shopian District, Jammu and Kashmir, India. Which was shown in Fig. 1A including the vetiver root used for root reinforcement studies. Figures 3 and 4 show the roots and field sampling wherein roots were collected and disturbed/undisturbed samples were obtained from.

The roots of plants can be collected by removing the subsoil with soil removal tools without damaging the roots. Plastic bags are used to wrap them and transport them to the laboratory without damaging the roots and soil. Once the roots have been separated, the plants are watered until the testing is complete. Plants are still alive during testing after the remaining roots have been removed. The roots continued to grow during this portion of the experiment.

3.4 Preparation of sample and lab procedure

Many trials were carried out using various strategies for homogeneous mixing of fibers with soil that have been documented in the literature After gradually mixing dry soil with fibers, the required water content was added, and the resulting samples were homogeneous. Each specimen's soil-fiber mass was poured into a split cylindrical mould and crushed into three layers, with each layer's weight and height carefully controlled. The differences in dry unit weight between treated and untreated soils were so slight that both reinforced and unreinforced soils were used. The samples were compressed with a dry unit weight of 11.8 kN/m^3 and a water content of 36%. The samples were then extruded and put in desiccators for 12 h to allow the moisture of the samples to equilibrate the soil used. The mass of soil fibers to keep the disparities in check, the extruded samples' length, diameter,

Fig. 1 **a** Location area. **b** soil samples. **c** Compaction Test. **d** Unconfined Compression Test. (Source: Google Earth)



(a) location area (Source: Google Earth) (b) soil samples

(c) Compaction Test (d) Unconfined Compression Test

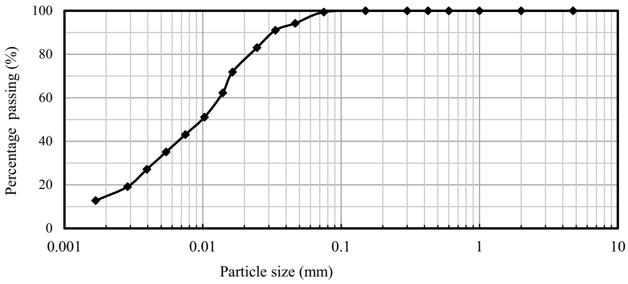


Fig.2 Particle size distribution curve

density, and moisture content are all factors to consider regularly for UCS soil samples before testing.

The UCS Test is regarded as one of the most effective methods for determining the importance of soil stabilization. The UCS test value (qu) is a valid parameter for determining how to implement and analyze different geotechnical projects requiring representative soil strength. Most past research has used specimens with dimensions of the standard size for UCS testing, which are 38 mm in diameter and 76 mm in length (Mickovski et al. 2005).

Different sets tests were used to explore the impact of various initial conditions on the behavior of both unreinforced and reinforced soils. All of the soil samples were compacted with MDU (11.8 kN/m^3) and OMC during the first series (36%), with fiber percentages ranging from 0 to 2.0% in 0.5% increments and for the different fiber lengths (20–25 mm) The size and composition of the fibers were both optimized as a result of this test series. As a result, the following test series focused on optimizing fiber length and composition. The density of the soil was chosen as a variable. In comparison, the other parameters remained constant. Soil density changed at MDU to assess the impacts of under compaction (Fig. 5).

Fig. 3 Plant and grass collection and their application on field

Fig. 4 Collection of samples at Mughal Road

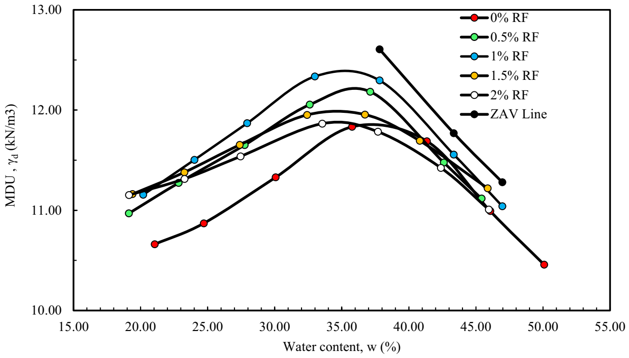


Fig. 5 Compaction curve of soil

4 Results and discussions

4.1 Field moisture content

Samples were collected from the site, and their field moisture content was assessed following the appropriate guidelines and the procedures specified in IS 2720, 1973 were followed, and the results are detailed in Table 1.

4.2 Specific gravity

Specific gravity is frequently needed in analyzing the soil for most of the geotechnical purposes Specific gravity was determined as per IS: 2720 (part 3) (Bureau of Indian Standards 1980) using density bottle and results are shown in Table 1.

4.3 Liquid limit test

For the determination of Atterberg limits, naturally dried by the air samples were passed by 0.425 mm by wet to dry process using Casagrande's cup method as per IS:2720 part 5 (Bureau of Indian Standards 1985) and the plasticity limit values were obtained as per IS: 2720 part 5 (Bureau of Indian Standards 1985) and results are shown in Table 1.

4.4 Proctor compaction test

The optimum moisture content (OMC) and the maximum dry unit weight (MDU) of the soil was obtained using the standard proctor compaction test as per Indian standard IS: 2720 part 7 (Bureau of Indian Standards 1980) and results are shown in Table 1.

Table 1 Untreated soil properties

Soil properties	Values	Soil properties	Values
Clay (%)	14	Clay (%)	14
Silt (%)	85.4	Specific gravity, G	2.50
Liquid limit (%)	64.70	Liquidity index	0.20
Sand (%)	0.6	Compression index, c_c	0.38
D_{30} (mm)	0.0044	Plastic limit (%)	41.80
D_{60} (mm)	0.014	Soil classification	MH
D_{10} (mm)	0	PI (A-line) (%)	32.70
Field water content (%)	46.30	PI (U-line) (%)	51
Field Bulk density (kN/m^3)	17.1	Clay mineral type	Kaolinite
Free swell index (%)	11.40	q_u (kN/m^2)	19.94
Plasticity index (%)	23	c_u (kN/m^2)	9.90
Angle of internal friction (φ)	23.94	Cohesion, c (kN/m^2) (DST)	6.52

4.5 Strength characteristics

For any soil strength parameters are very essential as stability and bearing capacity are much more dependent on these parameters. In present investigation two forms of strength analysis were conducted. i.e., Unconfined compressive strength (UCS) and shear strength. Unconfined compression test (UCT) and Direct shear test (DST) test were performed respectively to evaluate both the properties. UCT was performed according to IS: 2720-part 10 (Bureau of Indian Standards 1991) and DST test was performed as per IS: 2720-part 39 (Bureau of Indian Standards 1977) and results are shown in Table 1.

4.6 Proctor compaction test

The optimum moisture content (OMC) and the maximum dry unit weight (MDU) of the soil was obtained using the standard proctor compaction test as per Indian standard IS: 2720 (part 7) (Bureau of Indian Standards 1980). A plot between dry density and water content was drawn and OMC and MDD for the sample were obtained as shown in Fig. 5. The OMC and MDU of the sample were found to be 36% and 11.8 kN/m^3. The compaction curve is shown in Fig. 5.

4.7 Compaction effects on the root

Soil compaction has the potential to adversely impact crop growth and yield, both through direct effects and indirectly by exacerbating soil erosion or runoff. According to Bailen et al. (2019) virgin compression curves can be modelled using an equation accounting for water content. It is not always easy or possible to obtain virgin compression curve data. There are very few studies on the effects of roots on the compaction characteristics of soil, but in the present study, the author found that, as shown. As the concentration of root fibers increases, the maximum dry density decreases, as shown in the compaction curve diagram. There must be a reason for this since root fibre have a lower specific gravity. A special soil network is formed when fibre is added to the soil. In addition to adhesion, friction is also involved in its interaction with the soil. Loading mobilises soil fibers and prevents soil failure through friction and adhesion. Soil is also ductile due to fibers, in addition to being strong. Failure can be detected before damage occurs, which allows the engineer to take remedial measures to protect the structure. The fiber's length plays a crucial role. Its extent within the soil dictates the level of strength generated through friction at the interface between the fiber and the soil. This increased in value of MDD is due to the voids filling capacity of RF in the soil matrix. After 1% of RF is present in soil, MDD value decreases. RF particles may contain finer particles that have fewer voids than soil matrix particles. The excess RF causes the soil matrix to segregate, resulting in a decrease in the MDD value.

4.8 Permeability test

According to IS code 2720 (part 17) (1986), the falling head permeability test was conducted. The variation in permeability is shown in Table 2. When the percentage of root fibres in the soil sample increased, the permeability of the sample increased. Because of this, root fiber can be an effective

Table 2 Permeability results

RF (%)	Permeability constant, k (m/s)	Discharge, Q (m^3/s)
0	$2.30*10^{-8}$	$3.42*10^{-9}$
0.5	$1.34*10^{-8}$	$1.74*10^{-9}$
1	$5.13*10^{-9}$	$7.84*10^{-10}$
1.5	$3.96*10^{-9}$	$5.23*10^{-10}$
2	$4.96*10^{-9}$	$6.60*10^{-10}$

alternative for stabilizing slopes and preventing failures like soil erosion, landslides, etc. When root fibres account for 1% of the permeability coefficient, (k) increases. Previous studies did not consider the permeability of fibre-reinforced soil. However, observed a 1.5% increase in polymer permeability However, the permeability decreased for root fibre content greater than 1%. The average permeability test results are shown in the Table 2.

$$k = \left(2.303 * L * a * log_{10}\left(h_1/h_2\right)\right)/(A * \Delta t)$$

$$Q = k * i * A$$

4.9 Effect of plant roots on the permeability of soil

Depending on the configuration, orientation, and interconnections of root systems, live and dead components of root systems may increase or decrease the likelihood of shallow landslides during storms (Ghestem et al. 2011). The effects of changing the vetiver root content in soil on the permeability of soil samples with different densities are graphically depicted. The permeability of the root reinforced soil decreases with increasing vetiver root content for soil samples with densities of 1200 and 1450 kg/m^3. The effect of varying the vetiver root content on a soil sample density of 1600 kg/m^3 appears to be less well defined. The root system's sealing of void spaces in the soil can be linked to the overall decrease in permeability of soil samples, increasing vetiver root concentration. The decline in soil permeability, observed as lemon grass root content increases, is primarily caused by the root system filling and blocking void spaces within the soil. As a consequence, this process leads to a reduction in pore-water pressure within the root-reinforced soil. Ghestem et al. (2011) emphasized that such hydrological mechanisms, which contribute as a means of reducing soil pore-water pressure, are advantageous for enhancing slope stability.

However, it is more controversial to determine how plants affect soil permeability. Trees are widely accepted as enhancing soil permeability (Greenwood 2006), as reviewed by Chappell (2017). It has been shown that this is not universally true, as evidenced by a growing number of studies (Chappell 2017; Vergani and Graf 2016). The outcome varies based on the soil type and the soil's history of disturbance and vegetation cover type. The permeability test revealed both the permeability constant and soil discharge decreased when treated with root fibre. Plant roots improve the permeability of soil mass, according to the findings. This research might help decide which plant species to use and where they should be placed on a slope to achieve soil stability by lowering the permeability constant and increasing discharge by roughly. The findings indicate that soil permeability is enhanced by the presence of plant roots. These finding could prove beneficial in guiding the selection of plant species and their placement on slopes to promote soil stability.

4.10 Unconfined compressive strength

UCS tests are performed on the virgin soil sample left untreated as well as the sample treated with F%. These tests involve subjecting the soil samples to varying percentages of stress and plotting graphs correlating axial stress with axial strain (%) to identify the critical stress, as illustrated in Fig. 6. Unconfined compressive strength for the virgin soil treated with root fibre at various percentages is presented in Fig. 6. And similarly, undrained cohesion strength is given. A bar diagram is drawn for variation of unconfined compressive strength Vs portion of root fibre, as shown in Fig. 6, to compare the strength of virgin soil at various percentages.

4.11 Effects of root on UCS of soil

UCS are conducted according to IS: 2720 (part 10) (Bureau of Indian Standards 1991). As shown in Fig. 6, root fibre-reinforced soil exhibits stress–strain behaviour. Root fibre improves stress–strain behaviour. There is some tensile strength in root fibres, but not as much as in soil. Consequently, ductile behaviour of reinforced soil increases with fibre content along with peak stress. As shown in Fig. 6 Fiber content at different percentages affects the unconfined shear strength. With increasing fibre content, the UCS increases. It is found that the shear strength is maximum at 1.5%. As reported by Pattukandan Ganapathy and Palanisamy Saravanan (2015), fibre content also increased linearly over time. The shear strength of soil increases after mixing root fibre with soil, according to Danjon et al. (2008). Unreinforced and reinforced soils exhibit significant disparities in their

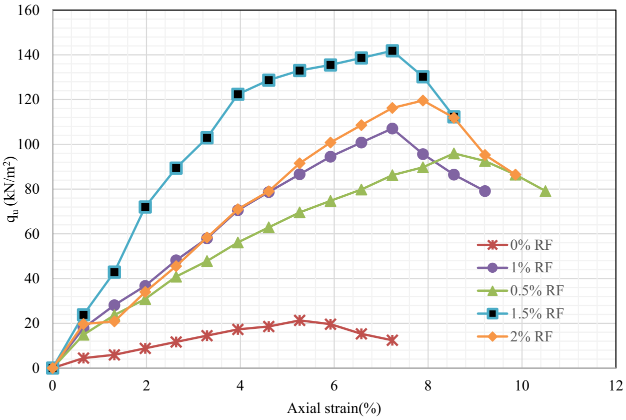


Fig. 6 Stress–strain curves of reinforced and non-reinforced samples at various fiber percentages

unconfined compressive strength (UCC); reinforced soil fiber blends demonstrate greater UCC strength compared to unreinforced clay. Incorporating 1.5% fibers by weight led to a doubling of the unconfined compressive strength compared to unreinforced soil. The composite's ductility also showed enhancement, as indicated by the stress-strain curve. Root fibers potentially enhance soil cohesiveness. The impact of root fiber attributes on stress-strain behaviour was found in Jan and Kumar (2022). The utilization of the UCS enhancement index was implemented to contrast the strength characteristics between soil samples without reinforcement and those with reinforcement. There's a considerable disparity in the UCS strengths between unreinforced and reinforced soils.; reinforced soil with fiber has a higher UCC strength than unreinforced clay. With the addition of 1.0% fibers by weight, the unconfined compressive strength increased to twice that of unreinforced soil. The composite's ductility has also improved, according to the stress-strain curve was found in the past study (Muirwood et al. 2016).

4.12 Possibility of root fibers may be used to improve soil cohesiveness

The stress-strain curve of untreated soil has a significant post-peak decline. As the fiber percent grows, the stress-strain curve changes proportionately. The peak's edges are on both sides. The stress–strain line curve's slope (secant modulus) gradually increases as the fiber percentage increases to 1.0%, suggesting a richer soil and fiber mass. Furthermore, the stress–strain curve's post-peak dip is significantly reduced, indicating that the fibers generate soil strain hardening. The axial strain at failure rises steadily up to the last point of fiber insertion (1.5%), showing that fiber root sample ductility is improving some of researcher have also find the same pattern (Mahannopkul and Jotisankasa 2019). The percentage of fibers that cross the failure planes creates a confining effect. An increase in overall strength due to the mobilization of fiber strength properties under more significant strains, and the interlinking of soil particles with fibers that produces a confining effect, are the main determinants of how soils interact with fibers. When the fiber fraction steadily increases, these soil-resistant plants become even more soil-resistant. Fiber interactions grow more visible until they reach a point where they have little or no repercussions.

Because the amount of fiber in the soil increases, there appears to be a degradation of contact across soil particles, resulting in a lack of soil matrix to keep fibers together and achieve adequate binding strength. This refers to the fact that the amount of fiber in a soil sample cannot be increased continuously and should be kept to a minimum. It is important to remember that the optimal having the UCS value alone should not be used solely to determine fiber content. While optimizing the fiber content, the uniformity of soil-fiber composites should also be addressed at greater fiber concentrations. The fiber in the range of 0.7–1.1% of the dry weight of soil was appropriate for laboratory research in the current study. Based on the above optimization standards, it was found that the UCS value climbed steadily at low fiber concentrations (up to 1.0%) when the fiber length increased from 10 to 20 mm. UCS values for samples made with 20 mm fibers are greater than those made with 20 mm fiber length. The improvement index for F: C 1.1% was doubled for fiber lengths of 10, 15, and 20 mm. For samples prepared with a 20 mm fiber length, the decrease in UCS value with increasing fiber concentration is due to incorrect fiber mixing, which leads to weak connections. The decline in UCS values for fiber lengths of 20 mm is mainly due to fiber clumping, which is more noticeable for longer fiber lengths.

Furthermore, blending this particular length was relatively simple, resulting in reasonably uniform samples. As a result, a 15 mm fiber length is appropriate for this sample size, approximately 42% of the sample diameter. A similar observation was made by Gray and Leiser (1982) finding that the best fiber length was 30 or 40% of the different sample diameters. On the other hand, Danjon et al. (2008) found that the ideal fiber length is around 50% of the sample diameter.

Reason for the change in the response of the stress-strain curve between the root reinforced and unreinforced soil

1. Soil Binding: As plants develop, a web of root fibers is formed by the roots' extension and dispersal across the soil. By acting as organic binders, these fibers keep soil particles together and improve the soil's overall stability.
2. Erosion Prevention: By firmly anchoring the soil, the root fibers lessen the possibility of soil erosion due to wind or water flow. This is particularly important in places that are prone to erosion, such as steep hillsides.
3. Improvement of Soil Structure: By forming pore gaps and channels, Soil structure is improved by root Fibers. As a result, the soil has better air and water circulation, which promotes microbial activity and root growth.
4. Water Holding Capacity: Root fibers improve soil structure and water infiltration, which in turn help the soil retain water longer. This is crucial because it keeps plants growing during dry spells, especially in desert or drought-prone areas.
5. Decreased Soil Compaction: By allowing roots to pierce and water to flow through, the root fibers can help reduce soil compaction. Roots can develop more freely and effectively by having easier access to nutrients and water in less compacted soil.

6. Natural and Sustainable Solution: Using root fibers to increase soil cohesion is an eco-friendly way to do it. It makes use of the natural processes of plant development and decay to lessen the need for chemical treatments or artificial additives.

4.13 Mechanics of microstructural failure and failure characteristics

In order to study how interfacial interactions affect the mechanical behavior of SEM tests were conducted on samples at optimum failure. Macroscopic images of failed samples were examined in order to determine their failure patterns.

4.14 Scanning electron microscopy (SEM)

The microstructure of materials determines their mechanical properties. To investigate the mechanical properties of materials, microanalysis is an invaluable method (Lawer et al. 2021) A study of the microstructure of the fibre-reinforced soil structure is therefore very important. Figure 7 shows the significant voids; soil particles are loosely bound in the untreated soil. However, in treated soil, voids are filled by fibres. The contact between fibre and soil improves the soil-fibre. Interactions between soil grains and fibres as well as understanding the mechanisms at work requires examining each soil-fibre matrix individually.

A soil-fiber column is created as soil particles less than fiber diameter, D_{50} Df, cling to the fiber surface, resulting in soil-fibre columns. Figure 7 shows that dirt granules remain adhered to the fibre surface even after the specimens have been sheared, as seen in Fig. 7. In this way, it can be demonstrated that the soil is capable of transmitting stress through its fibre column. Because of the soil's natural strength and the mobilization of fiber's tensile strength. This soil-fibre network develops when soil specimens' fibre concentration rises, leading to superposition and stress transfer over a broader space (Gao et al. 2015). Moreover, certain soil particles become attached so tightly onto the surface of the fiber, causing pits and grooves can be seen in the SEM micrographs. Increasing fiber surface abrasion produces better fiber interfacial conditions due to the impaction of particles. Interlock resistance (Anagnostopoulos et al. 2014). Despite this, no obvious cracks can be seen due to the failure plane resulting from these micromechanical interactions. As the sample swells, hairline cracks are apparent, indicating a change from brittle to plastic.

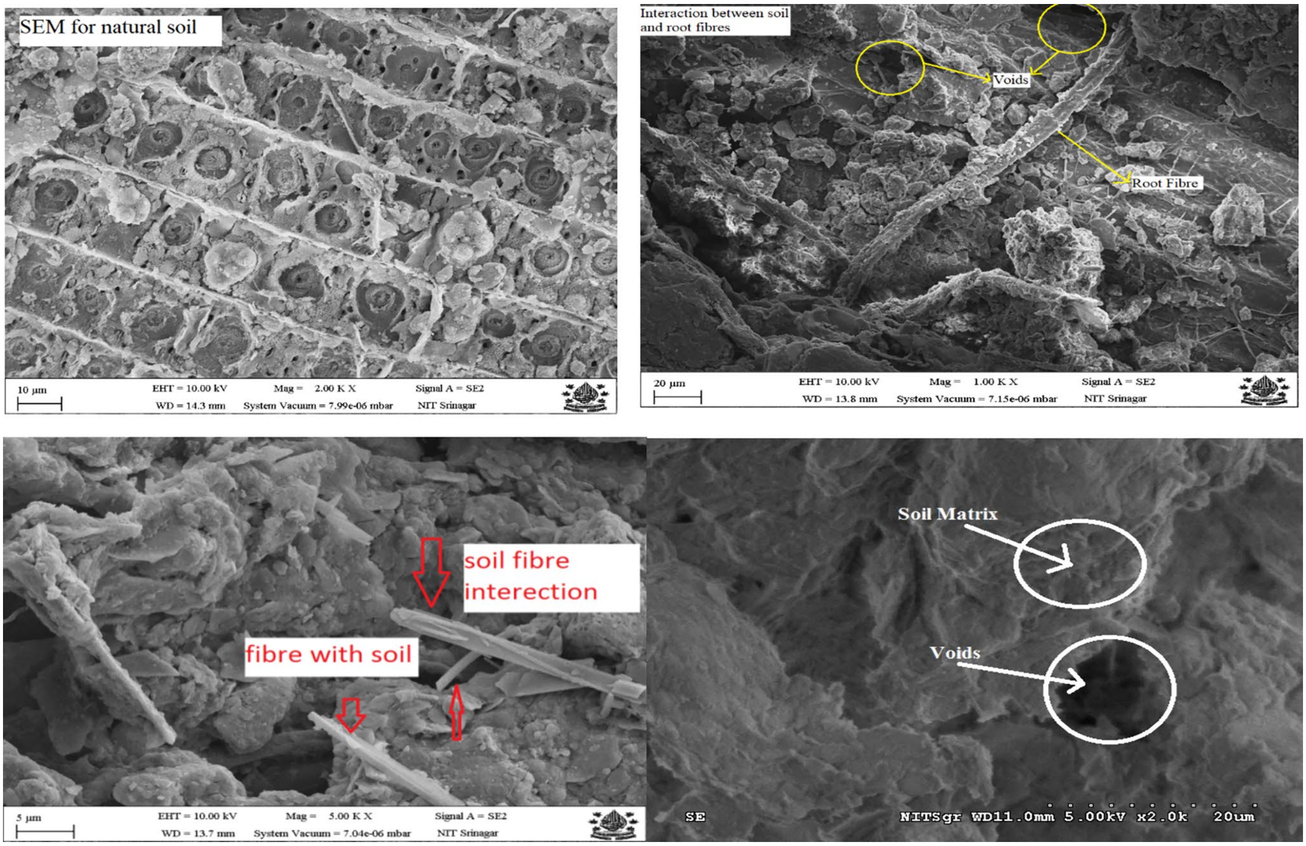


Fig. 7 Interaction of soil with root SEM images

4.14.1 Direct shear test

Direct shear tests for the soil samples of untreated and treated with root fibre are conducted, and graphs are plotted between shear stress and strain for calculating the failure shear stress. For calculating the DST parameters, namely cohesion and angle of internal friction, graphs are plotted between shear stress and normal stress and DST parameters are thus calculated from graphs as shown in Figs. 8 and 9.

In this research work, strength parameters are found by conducting the Direct Shear Test by taking the maximum size of the soil sample of 4.75 mm. DST parameters, Cohesion and angle of internal friction of treated soils (Figs. 10, 11).

4.14.2 The impact of roots on shear strength parameters

Shear failure is the most common cause of soil failure, so it's important to evaluate it. These studies discovered that increasing root mass in the soil results in a significant increase in shear strength. The shear strength is measured on undisturbed soil samples, so the increase in the roots' tensile strength and root biomass are exclusively responsible for shear strength. According to test results, soil strength parameters increased by 2% when RF was added, due to soil cohesion being increased by RF a decrease in strength parameters was reported when 2.5% of RF was added to the soil. This could be due to soil particles flocculating, resulting in a change in gradation. The combined effects of cohesion and adhesion induced by the root matrix lead to an overall increase in soil stability and better resistance against erosion. Understanding the role of root systems in enhancing soil strength is of paramount importance for soil and slope management, ecological restoration, and engineering practices aimed at mitigating soil-related hazards (Haji and Osmani 2008). Researchers observed an average increase of 119% in cohesion (c′) and 12% in the angle of internal friction (ϕ′) due to the presence of grass roots (Cardoza and Oka 2020).

4.15 CBR test

The California Bearing Ratio test is a commonly employed technique to evaluate the strength of subgrade soil and various pavement materials. CBR represents the proportion of load necessary to penetrate a standardized circular piston into a soil sample at a rate of 1.25 mm/min, compared to the load required for the equivalent penetration of a standard material. This ratio is expressed as a percentage IS 2720 (part 16) (Bureau of Indian Standards 1987). Samples were examined under both soaked and unsoaked conditions. To facilitate soaking, the CBR mould, along with a surcharge weight of 4.54 kg, was immersed in a water bucket. This ensured that water freely entered the sample from both the top and bottom ends. The samples were cured for 7 days and subsequently soaked for a period of 96 h prior to testing (Figs. 12, 13, 14; Tables 3, 4).

4.16 Effects of fibre contents on the CBR

Figure 15 shows how CBR varies with fibre content when it is soaked. According to this plot, the CBR value of expansive soil improves with an increase in fibre content after adding fibres. After 1% fibre content, peak load increases

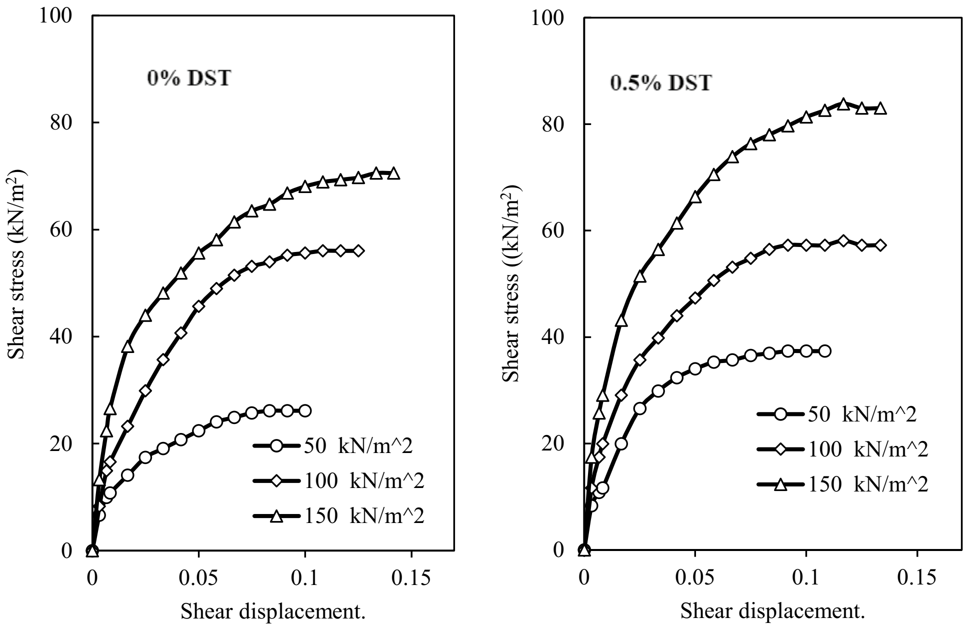
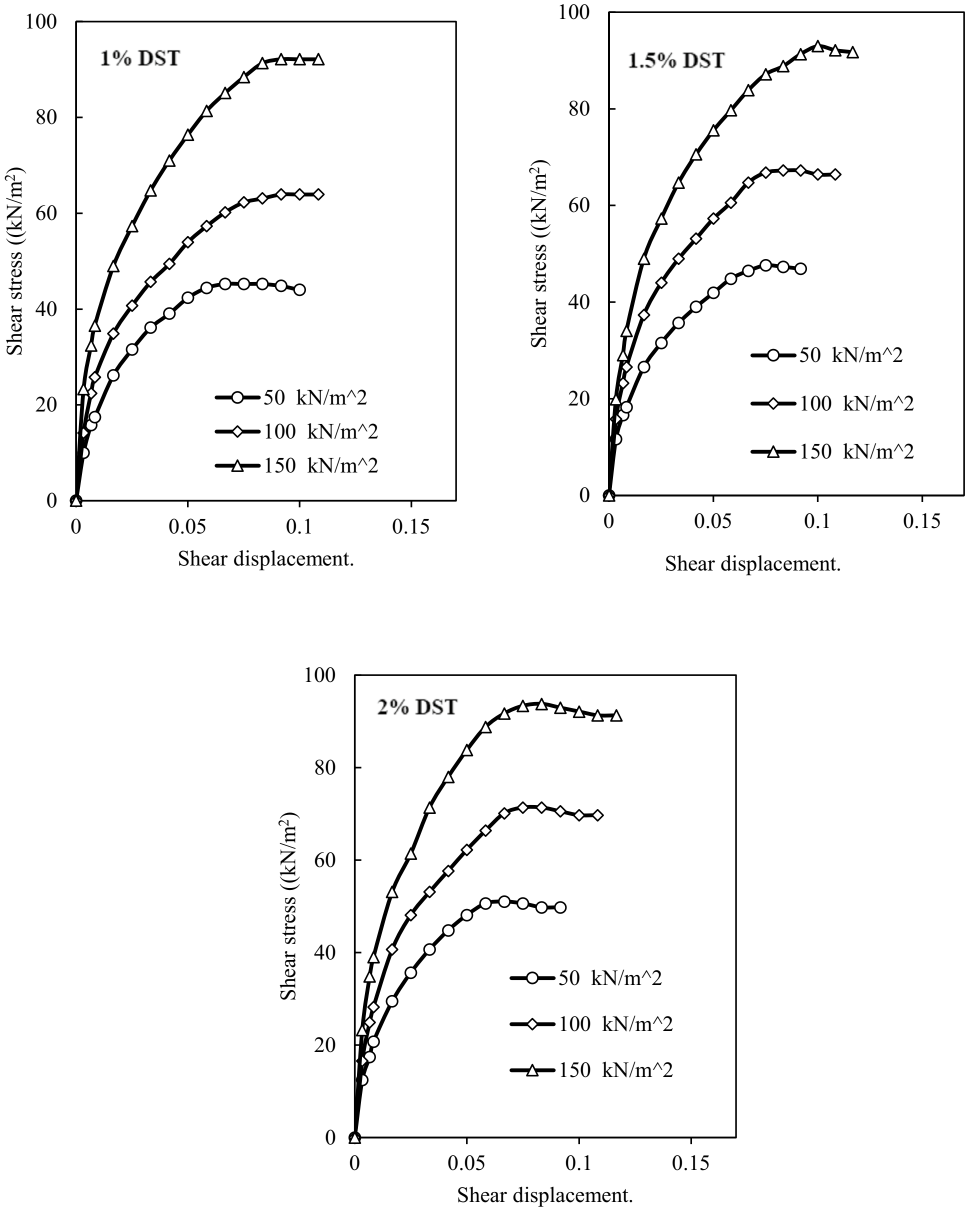


Fig. 8 DST curves between shear stress v/s shear displacement for unreinforced and reinforced soil treated with root fibre

Fig. 9 DST curves between shear stress v/s shear displacement for unreinforced and reinforced soil treated with root fibre



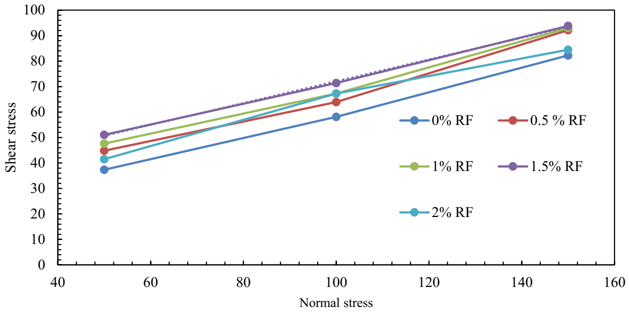


Fig. 10 Variation in Mohr-Columb failure envelops at different percentage of RF

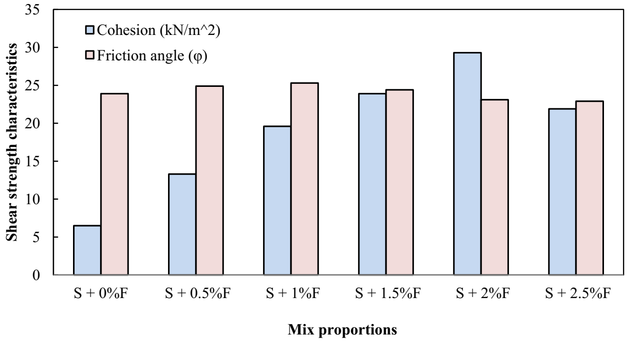


Fig. 11 Cohesion v/s friction angle for unreinforced and reinforced treated with root fibre

Fig. 12 Load penetration curve for varying root content

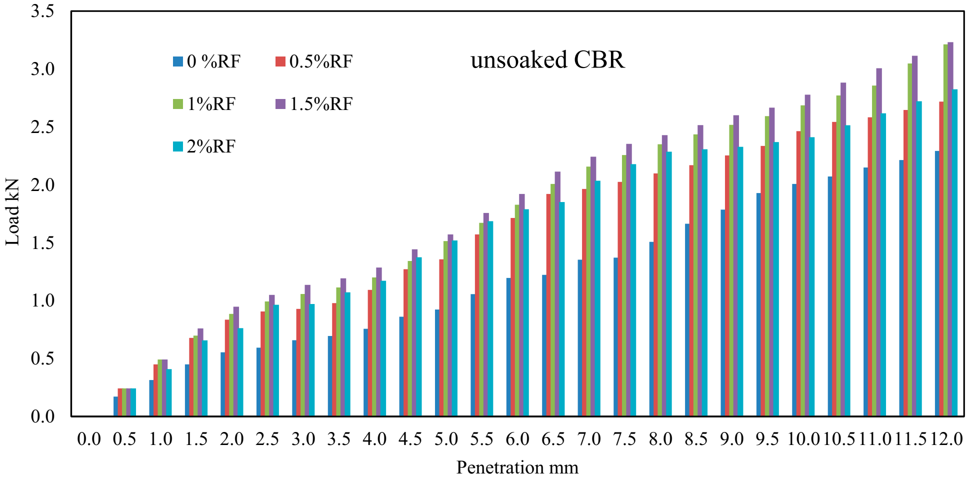


Fig. 13 CBR v/s percentage root content curve

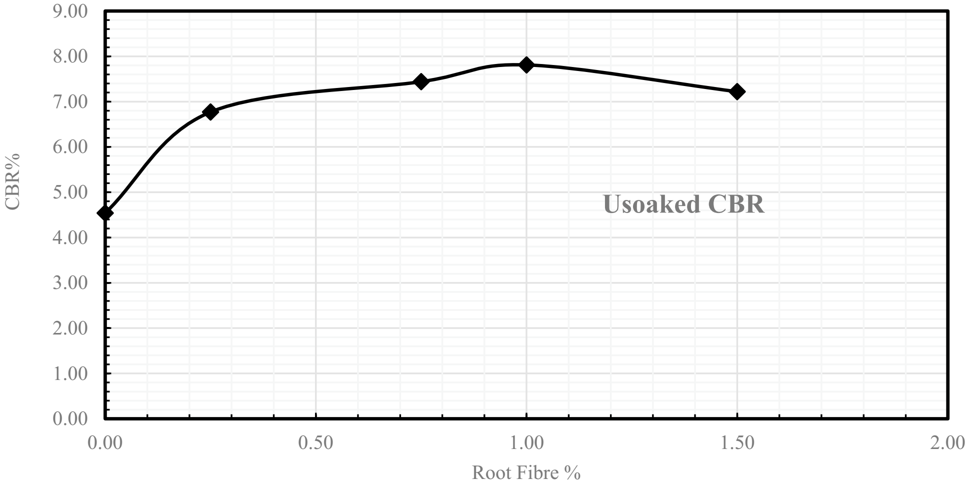


Fig. 14 load penetration curve for varying root content

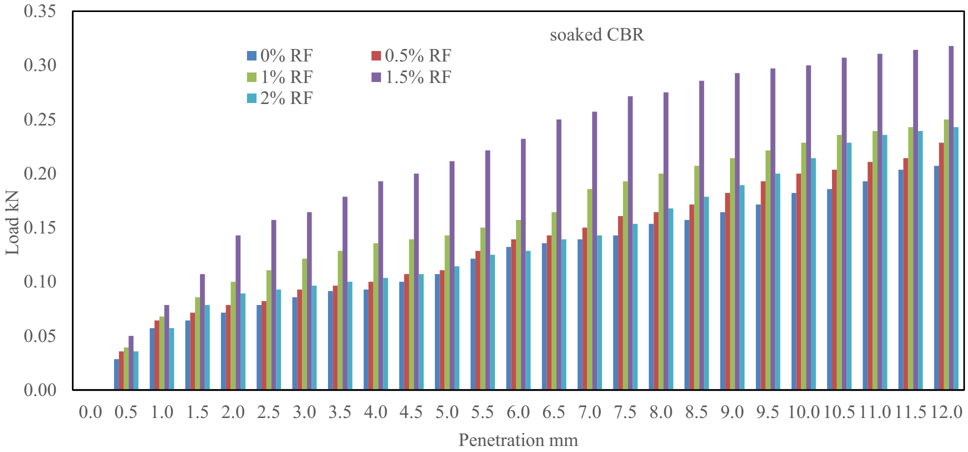


Table 3 CBR variation v/s root contents

Root content	Untreated soil	0.25%	0.75%	1%	1.5%
CBR %	4.54	6.77	7.44	7.81	7.22

Table 4 CBR variation vs root contents

Root content	Untreated soil	0.25%	0.75%	1%	1.5%
CBR %	0.42	0.49	0.56	0.87	0.45

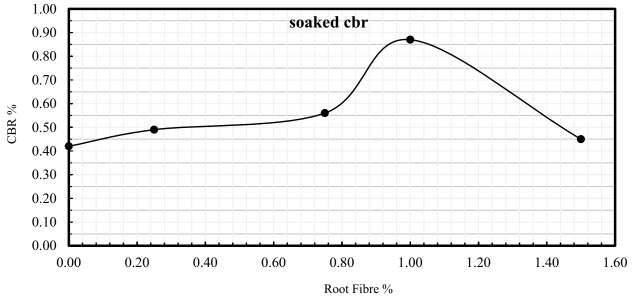


Fig. 15 CBR v/s percentage root content curve

and then decreases as fibre content increases. As a result of improved interfacial adhesion between soil particles and fibers, the CBR value has increased due to more efficient load transfer at the soil fiber interface. Adding fibres to the soil increases its load bearing capacity by making the soil more resistant to soil movement. As fibre content increases beyond 1%, fibre-to-fibre interactions increase and soil-to-fibre interactions decrease since soil particles are replaced by more fibres resulting in lower CBR values. At 1% fibre content, fibres are unable to maintain an effective bond with soil due to insufficient soil quantity and difficulty mixing fibres with soil (Ramjiram Thakur et al. 2021) have conducted reinforced with randomly distributed jute fibres revealed the following conclusions based on California Bearing Ratio tests: Randomly distributed jute fibres significantly improved the CBR value of expansive soil. At 1.25% fibre content, jute fibre inclusion gives the highest CBR value for reinforced soil, then it decreases with increasing fibre content. A soil sample obtained in the unsoaked condition has a higher CBR value than a soil sample obtained in the soaked condition.

4.17 Limitation of bio soil engineering

Bio-soil engineering, also known as biotechnical slope stabilization, is a nature-based approach to slope stabilization that utilizes vegetation, especially grass roots, to enhance the stability of slopes. While this method can be effective in certain situations, it also has some limitations.

1. Soil nature and Slope Gradient: The kind of soil and slope gradient affect how effective biosoil engineering is. The grass roots may not give adequate support to stop erosion and slope failure on steeper slopes or in poorly cohesive soils.
2. Establishment Period: Using bio soil engineering techniques often takes some time to allow plants to take root and grow a robust canopy. This establishing phase leaves the slope susceptible to instability and erosion.
3. Maintenance Requirements: The long-term viability of bio-soil engineering depends on the vegetation being maintained. It is necessary to perform routine maintenance, including pruning, weeding, and erosion control techniques, to guarantee that the slope is sufficiently stabilized by the grass roots.
4. Plant Species Selection: The effectiveness of bio-soil engineering depends on the selection of plant species. The plants that are chosen should be able to flourish in the site's conditions, have a strong root system, and stabilize the soil.
5. Site-Specific elements: Climate, soil properties, hydrology, and slope geometry are among the site-specific elements that affect the effectiveness of bio soil engineering. What is effective in one place might not be in another.
6. Limited Effectiveness in Significant impact Events: In regions vulnerable to catastrophic weather events such as intense downpours, landslides, or severe floods, bio soil engineering might not be able to offer enough stability.
7. Land Use and Room Constraints: Because bio-soil engineering requires enough room for vegetation to develop and root systems to form, it may not be practical to execute it in urban settings or regions with limited space.
8. Invasive Species: Adding specific plant species to stabilize a slope may have unforeseen repercussions, such the development of invasive species that harm the surrounding ecology.
9. Limited Effectiveness in Significant Impact Events: Bio soil engineering may not be able to provide enough stability in areas susceptible to catastrophic weather events like heavy downpours, landslides, or severe floods.
10. Land Use and Space Constraints: Bio-soil engineering may not be feasible in urban areas or areas with restricted space since it needs sufficient space for plants to grow and root systems to form.
11. Invading Species: Adding particular plant species to a slope's stabilization may have unintended consequences, like the emergence of invading species that damage the ecology of the area.

Despite these limitations, bio-soil engineering using grass roots can still be a valuable and sustainable approach to slope stabilization in many situations, especially when combined with other stabilization techniques in an integrated and adaptive management approach. Before implementing this method, a thorough site assessment and understanding of the specific conditions and limitations are crucial for its successful application.

As the field of bio-soil engineering continues to evolve, there are several future recommendations and advancements that can further enhance the effectiveness of using grass roots for slope stabilization:

4.18 Future recommendations for research work

1. Studies and Development: It is imperative that the discipline of bio-soil engineering continue to be the focus of research and development. This entails examining the root systems of several plant species to determine which have the best root features for stabilizing slopes. Improved vegetation selection may result from knowledge of these roots' interactions with the soil and their environmental adaptations.
2. Native Plant Selection: It is essential to encourage the use of native plant species in bio soil engineering. The risk of importing invasive species is decreased by native plants, which have established ties with local ecosystems and are better adapted to the local environment. Prioritizing research on native plant species and their aptitude for stabilizing slopes is a good idea.
3. Integration with Erosion Control Techniques: Integrating bio-soil engineering with other erosion control techniques, such as erosion blankets, mulching, and geotextiles, can accelerate the establishment of vegetation and provide additional stability during the critical establishment period.
4. Monitoring and Data gathering: To comprehend the performance of biosoil engineering projects throughout time, long-term monitoring and data gathering must be implemented. This data can be useful for future studies and can assist improve species selection and design approaches.
5. Climate Resilience: Considering the potential impacts of climate change on vegetation and soil conditions is vital for ensuring the long-term stability of bio-soil engineering projects. Selecting plant species that are resilient to changing climate patterns can improve the durability of the slope stabilization efforts.
6. Adaptive Management: Adopting adaptive management approaches allows for the flexibility to adjust and improve bio-soil engineering projects over time based on real-time monitoring and data. This approach facilitates learning from successes and failures and helps to refine strategies for future projects.
7. Cooperation and Knowledge Sharing: Promoting cooperation amongst academics, professionals, and decision-makers can help to advance the sharing of best practices and knowledge in the field of biosoil engineering. The implementation of this sustainable slope stabilization method can be accelerated by exchanging successful case studies and experiences.
8. Education and Outreach: It's critical to raise landowners', engineers', and communities' knowledge of the advantages and constraints of bio-soil engineering. The adoption of this nature-based approach should be encouraged and misconceptions can be helped by public outreach and educational activities.
9. Regulations and Incentives: By offering incentives or enforcing rules that stimulate the use of natural slope stabilization techniques, governments and municipalities can significantly contribute to the advancement of bio-soil engineering.

By putting these suggestions into practice in the future, biosoil engineering with grass roots can become a more practical and long-lasting method of stabilizing slopes, helping to reduce erosion, restore ecosystems, and increase the resilience of landscapes overall.

4.19 Conclusion

The addition of roots as a root matrix is proven to be a promising approach for boosting both strength and stability qualities in this study.

- Bio-engineering techniques show immense promise in potentially replacing current soil reinforcement and improvement methods used for enhancing marginal soil or controlling erosion.
- It's also been found that the roots absorb some of the water provided to the soil particles, resulting in higher OMC values and a higher root percentage. This is consistent with the findings of previous researchers who increased shearing resistance by using diverse natural roots in the soil.
- Based on the permeability test results, it can be observed that treating marginal soil with RF (presumably a treatment or additive) leads to a reduction in both permeability constant and discharge. This decrease can be attributed to the presence of fine material in the RF, which fills up the free voids within the marginal soil. Consequently, at just 1% RF content in the marginal soil, the permeability constant and discharge decrease significantly, by approximately six times.
- The permeability of the soil has been observed to decrease continuously as root content increases; this decrease in permeability results in higher density and shearing resistance. The investigation is carried out with varied densities to check the correctness of the loss in hydraulic characteristics. It is discovered that, in addition to densification of soil, roots contribute to a more significant drop in permeability.

- Both reinforced and unreinforced products have an increased UCS value with increasing dry unit weight for a given fiber and moisture content.
- As the root content in the soil increases, there is a continuous and gradual improvement in shearing resistance. This enhancement can be attributed to the formation of a fiber matrix generated by the roots. With increasing density of this matrix and variations in the fibers, the strength of the soil also increases.
- However, one potential issue associated with incorporating roots into the soil is the degradation of the roots over time. This concern applies to any type of roots added to the soil. Despite this, the degradation of the soil-root matrix can lead to the creation of humus, which might actually contribute to greater stability.
- Thus, it is concluded that computational soil improvement techniques like the application of grout, cement, lime etc, are proving to be hazardous to the environment. There is a need to introduce/apply some natural, sustainable soil improvement techniques and the use of roots as a method to stabilize landslide slopes is one of the most environmentally friendly methods.

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Data availability All data can be made available on request to the corresponding author.

Declarations

Conflict of interest Not applicable.

Ethical approval This article does not contain any studies with human participants or animal performed by any of the authors.

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