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TECHNICAL PAPER

Strength Behaviour of Marginal Soil Reinforced with Grass Roots

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Abstract

The roots of vetiver grasses can act as a reinforcement and reduce the intensity of slope erosion by protecting the slope from raindrop impact through the anchorage effect and by improving the physio-mechanical behaviour of the soil. This study examined the influence of roots on the shear strength of silty clay soils. Grasses of native species of the Himalayan forest were used as soil reinforcement in the present experimental study. The study concentrates on the shear strength enhancement and improvement in the physical characteristics of the soil-root matrix. Root content has been varied from 0 to 2.5% with an increment of 0.5%. The soil cohesion is found to improve significantly compared to enhancement in the angle of internal friction. The reinforced soil exhibits improved stress-strain behaviour and ductility of soil. These results can serve as a technical basis that can support the utilisation of locally available environmentally friendly grass roots for erosion control and slope stabilisation.

Keywords Slope stabilisation · Direct shear test · Unconfined compressive strength · Vetiver root · Compaction

Abbreviations

IS	Indian Standard
CH	Clay with high plasticity
CI	Clay with intermediate plasticity
CV	Clay with very high plasticity
DST	Direct shear test
SEM	Scanning electron microscope
K	Kaolinite
M	Montmorillonite
ME	Silt with extremely high plasticity

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MH	Silt with high plasticity
MI	Silt with intermediate plasticity
ML	Silt with low plasticity
MV	Silt with very high plasticity
OMC	Optimum moisture content
MDU	Maximum dry unit weight
MDD	Maximum dry density

Notations

RF	Root fibre
RFS	Root fibre soil
ZAV	Zero air void line
LL	Liquid limit [%]
PI	Plasticity index (= LL – PL) [%]
PL	Plastic limit [%]
SI	Shrinkage index (= LL – SL) [%]
C	Cohesion
φ	Angle of internal friction

1 Introduction

Landslides, characterised by the failure of sloping earth material, represent a highly prevalent geophysical phenomenon. Due to their significant impact, they stand out as a critical concern in geotechnical engineering. Notably, landslides rank among the most financially and humanly costly disasters. In recent times, the occurrence of natural slope instability has witnessed a rise, particularly in tropical monsoon regions, such as those found in Southeast Asian countries. In ancient times, vegetation was used to stabilise slopes. The contributions of vegetation to several particular geotechnical processes have recently come to light. In several ways, vegetation may affect the stability of a slope. Slope stability is determined by two main factors: the load, which triggers failure, and the resistance, which represents the soil-root system strength. When trees grow on a slope, their weight contributes to the load, while their roots act as reinforcements and enhance the resistance. Furthermore, vegetation indirectly affects slope stability by impacting the soil moisture levels. Vegetation intercepts rainfall and extracts water from the soil through evapotranspiration, leading to reduced soil moisture and pore pressure. As a result, the soil shear strength increases, ultimately bolstering the resistance. There has been an increase in interest in studying soil-root composites with regard to their mechanical strength due to our understanding of the role roots play in soil reinforcement. It has been shown that studies of this type are important mainly because root maintenance is increasingly recognised as a method that is simple, effective, and economically viable for controlling erosive processes and surface mass movements; regeneration can occur naturally or through specific planting techniques (Gray et al., 1996). Many previous studies (Mahannopkul & Jotisankasa, 2019) have made assumptions that the root tensile strength and the additional shear strength provided by roots (root cohesion) were unaffected by suction and remained constant over time. While the underlying principles and understanding of root reinforcement mechanisms are straightforward, effectively quantifying and integrating the biological impacts into conventional slope stability assessments remains a significant hurdle. This poses a notable drawback for soil bioengineering techniques (as highlighted by (Graf & Frei, 2013)) when compared to firmly established methods in conventional civil engineering, such as the design and calculation processes for structures like retaining walls or soil nailing. In previous studies (Maleki et al., 2022), various numerical approaches, including the finite element method, have been employed to investigate the performance of a 10 m tall restrained wall using the nailing method under pseudo-static seismic analysis. Slope stability studies require the determination of soil strength, which is typically accomplished by shear strength tests. Based on the Mohr-Coulomb failure criterion, this analysis is completed. This is depicted by the equation (($\tau = c + \sigma_n \tan \phi$) according to (Deng et al., 2023). According to this standard, the soil cohesiveness (c) and the angle of internal friction are the variables the roots can affect. The foundation design-based mitigation measure has proven to be significant. Additionally, this study makes a unique contribution by conducting a parameter analysis on the interaction between soil and structure under vertical vibration, which is distinct from most studies that typically focus on horizontal forces (Mahannopkul & Jotisankasa, 2019).

The widely accepted notion that roots significantly contribute to soil reinforcement has sparked an increasing interest in investigating the mechanical strength of soil-root composites. This line of research has gained importance because the maintenance of roots within the soil, whether through natural regeneration or deliberate planting techniques, is increasingly acknowledged as an effective, straightforward, and economically viable approach for controlling erosive processes and surface mass movements (Gray & Leiser, 1992). Many previous studies have attempted to assess changes in shear strength using various slope stability methods. In this study, the researchers employed a numerical modelling approach, specifically the finite element modelling method, to analyse the lateral earth pressure on a rigid retaining wall close to the stable rock face. Assessing soil strength is fundamental in slope stability studies, and shear strength tests are commonly employed for this purpose. This analysis often uses the linear equation that represents the Mohr-Coulomb failure criterion ($\tau = c + \sigma n \tan \phi$). According to this criterion, the cohesion (c) and angle of internal friction (ϕ) of the soil are the parameters that the presence of roots can influence. Previous research involved conducting a series of seismic analyses using a two-dimensional plain-strain model created with the Plaxis software. The numerical model was initially derived from a man-made trench wall situated in downtown Tehran, the capital city of Iran (Maleki & Nabizadeh, 2021).

Studies showing the importance of bioengineering in stabilising soil masses have been put forth by researchers wherein they credited the stabilisation process to various factors like microbial processes and vegetation covers including the effects of root density, area ratio, length, and root types (Wani & Mir, 2022; Wani & Mir, 2021). Using moulded and laboratory-prepared soil samples has shown that roots significantly increase shear strength primarily by affecting the cohesive intercept, with little change observed in the angle of internal friction (Haji & Osmani, 2008).

However, validating whether these findings align with real-world conditions is crucial. To achieve this, it is essential to determine the shear strength of various root-soil combinations using undisturbed samples collected in their natural environment (in situ). This consideration ensures that the results reflect the actual field conditions accurately. In experiments with lab-prepared soil samples and moulded soil samples, the influence on the cohesive intercept is primarily responsible for enhancing shear strength due to root inclusion, while the angle of internal friction exhibits little or no change (Gao et al., 2015). This type of information must be verified in practice to ensure that it matches the reality on the ground. Consequently, it is essential to determine the shear strength of root-soil composites should be measured using in situ sample collection. Using silty clay soil and silty clay soil, we evaluated the impact of roots on soil reinforcement so that we could contribute information about how plants reinforce soil. In the past, numerous studies have primarily emphasised slope stability analysis through numerical modelling or laboratory techniques, focusing on wall movements (Maleki & Imani, 2022).

Previous research has extensively examined the stability and deformation of deep excavations when reinforced with the nailing method through static analysis (Maleki & Hosseini, 2022). In accordance with the findings, an increase in the length of the nails leads to several noteworthy outcomes. First, it reduces both the maximum lateral deformation of the wall and the maximum force experienced by the nails. Simultaneously, this increase in nail length contributes to an improvement in the safety factor. This phenomenon can be attributed to lengthening the nails, extending them further into the area beyond the failure wedge. Consequently, the failure wedge establishes a more stable connection with the soil situated behind it. Furthermore, as the nail length increases, there is a corresponding rise in the frictional forces occurring at the interface between the nails and the soil located behind the failure wedge.

The angle of internal friction of the silty clay soil exhibited only a minor alteration due to the presence of roots. Research has shown that the presence of roots can result in slight adjustments in the positioning of soil particles (Graf & Frei, 2013). This phenomenon is typically associated with the relatively small number of roots typically found on the failure surface. In the uppermost soil layers, particularly within the top 50 cm, where root density is higher, studies have consistently reported that the root rate per unit area of soil (referred to as root area ratio—RAR) tends to remain below 1%. This means that approximately 99% of the failure surface primarily consists of soil. This proportion helps explain why soil sections with a limited presence of roots exhibit minimal changes in the arrangement of soil particles and consequently have only a minor impact on the angle of internal friction.

The main objective of this study was to assess the impact of locally available grass roots on the shear strength of silty clay soil, aiming to provide valuable insights into the reinforcement effect of grass roots on the soil. The aim of this paper is to present a research initiative focused on evaluating the efficacy of implementing the vetiver root-reinforced system to enhance slope stability. The investigation involves employing a laboratory technique to assess the shear strength parameters of soils reinforced with vetiver roots. A number of shear strength tests were conducted to determine the shear strength parameters. This indigenous grass, readily found in the area, reaches full growth in just 2 months, which is a relatively short timeframe.

The abundance of this locally available grass means no direct costs are associated with its use. It has been observed that this approach is highly cost-effective.

1.1 Objective of This Research

The objective of stabilising soil using grass root fibres as reinforcement is to improve the engineering properties of the soil and increase its overall stability. Grass root fibres, when incorporated into the soil, act as natural reinforcements, which can enhance soil strength, shear resistance, and cohesion. This technique is often employed in geotechnical engineering and civil construction projects to address soil instability issues and prevent potential problems like erosion, landslides, or settlement. Some of the main objectives of stabilising soil with grass root fibres include the following:

1. Increased shear strength: The grass root fibres interlock with the soil particles, providing additional resistance against shear forces. This helps to reduce the potential for soil failure and improves the overall stability of slopes and embankments.
2. Erosion control: Grass root fibres help to bind the soil particles together, reducing the risk of soil erosion caused by water or wind. This is especially important in areas with high rainfall, steep slopes, or vulnerable soil conditions.
3. Settlement reduction: By reinforcing the soil, grass root fibres can help distribute loads more evenly and reduce settlement or subsidence issues in weak or compressible soils.
4. Sustainable and environmentally friendly solution: Using grass root fibres as reinforcement is a natural and eco-friendly approach to soil stabilisation, as it does not involve the use of synthetic materials or chemicals that may have adverse environmental impacts.
5. Cost-effectiveness: Grass root fibres are often readily available and can be obtained at low or no cost. This makes the stabilisation technique economically viable, especially in rural or agricultural areas.
6. Flexibility: Grass root fibres can be applied in a variety of soil types and can adapt to different environmental conditions, making them a versatile choice for soil stabilisation.

It is important to note that while grass root fibres can provide some level of stabilisation, their effectiveness may vary depending on the specific soil conditions, types of grass used, and other factors. In more critical applications or challenging soil conditions, additional reinforcement methods or materials may be necessary to achieve the desired level of stability.

1.2 literature Review

Studies using moulded and laboratory-prepared soil samples have shown that roots significantly increase shear strength primarily by affecting the cohesive intercept, with little change observed in the angle of internal friction (Haji & Osmani, 2008). Numerous prior investigations serve as examples, wherein researchers aimed to quantify alterations in shear strength parameters resulting from the integration of grass roots within the soil. (Tengbeh, 1993) conducted experiments to assess the impact of grass on clay and sandy clay loam soils, revealing that both soil types exhibited a substantial 500% increase in shear strength. In the research conducted by (Hamidifar et al., 2018), an examination of the soil-root system for Vetiver grass in silty clayey soil was conducted, leading to the observation that grass roots contributed to a significant 119.6% increase in cohesion and an 81.96% increase in the angle of internal friction. The researchers additionally highlighted that root area ratio (RAR) and root length density (RLD) exhibited the most robust correlation with the soil shear strength parameters.

Multiple instances of prior research exist where scholars have aimed to measure the alterations in shear strength parameters resulting from the incorporation of grass roots into the soil. An example of such work is the study titled *Experimental Studies on Soil Stabilization Using Vetiver Root as Reinforcement* (Ganapathy et al., 2015).

Hence, taking into account the available literature, it becomes apparent that grass roots exert an influence on shear strength parameters (Table 1). Nevertheless, a unanimous agreement on whether it can be precisely modelled is still lacking due to the intricate interactions among multiple variables. As a result, the choice was made to employ an empirical method and directly evaluate how grass roots affect shear strength parameters in silty clay soils.

2 Material and Methodology

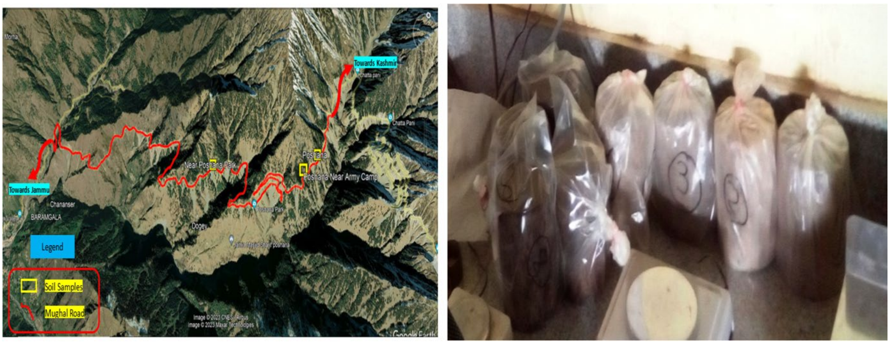
2.1 Soil Sample Collection

Samples of different soil were collected in distinct regions of the state of Jammu Kashmir, India, along the Mughal Road, which connects the entire region of Kashmir, as shown in Fig. 1a.

The research specimens were collected from the districts of Poonch and Shopian, located in Poshana and Dubjan, respectively, along the historical Mughal route. This route was once utilised during the Mughal Empire to connect the Kashmir Valley with the rest of India. To avoid grass and plant roots mingling in the soil, soil samples have been collected disturbed, and undisturbed soil samples that have not been collected were 1 m beneath the ground surface. Great care was taken when collecting metal cores from the soil to ensure that the structural integrity of the samples was preserved. Plastic bags were used to wrap the cores to maintain the soil natural moisture content. The soil was dried in the oven, crushed, and sieved with a 2 mm IS standard sieve for the laboratory. Samples of undisturbed soil with roots were collected in the mentioned areas through metal cylinders with a diameter of 10 cm and a length of 20 cm. One end of the cylinder was sharpened to facilitate penetrating the cylinder into the soil. An applied load was centrally distributed by inserting a 2 kg metallic weight into the soil. The cylinder was placed in the intended spot and struck until it was fully embedded in the ground. The surroundings around each

Table 1 Validation of proposed study through available literature

Authors	Year	Sample	Fibre length (mm)	Cohesion (Kpa) c=	Improvement of cohesion (%) C =	Angle of internal friction Φ	Improvement of shear strength parameter %
Present study		Vetiver root	20–25	23.9	65	26.37	11
(Maffra et al., 2019)	2019	Atlantic forest native species	Field test	7.2	119	27.9	21
(Teerawattanasuk et al., 2014)	2014	Vetiver and ruzi grasses	25–30	21.2	32	6.51	14
(Cazzuffi & Crippa, 2005)	2006	Era grass, Ely grass, vetiver and -an grass	Field test	14.6	250	-	-
(Kumar et al., 2022)	2022	Vetiver root	15–20	21.22	87	31.29	18
(Gobinath et al., 2015)	2015	Vetiver root	20–30	5	48	28	72
(Cardoza et al., 2020)	2020	Vetiver root	Randomly distributed	10	119	39	12

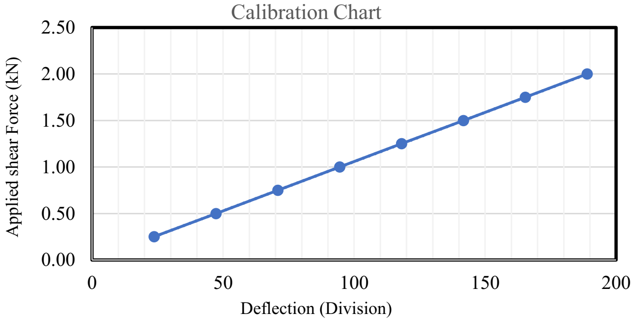


(a) sample location area (Source: Google Earth)

(b) soil samples

(c) Compaction Test

(d) Unconfined Compression Test



(e) Device Calibration DST

Fig. 1 **a** Sample location area (Source: Google Earth). **b** Soil samples,. **c** Compaction test. **d** Unconfined compression test. **e** Device calibration DST

chosen plant were then sampled at 4 locations up to 20 cm deep, between 10 and 20 cm from the stem. The cylinders were taken out with a shovel and hoe after this sampling. The ends of the cylinders have been covered with heated paraffin in order to preserve the natural soil moisture (field moisture). On the days of the direct shear testing, samples with measurements of 6 × 6 × 2 cm were made in the lab using the collected cylinders. Each gathered cylinder could produce 3 to 4 specimens in the moulding process. Small excavations 2.5 m away from the plants were used for the sample-collecting efforts without roots. Figure 1d depicts the UCS test setup and corresponding calibration chart.

The soil was adjusted using a core cutter to the necessary depth (between 15 and 20 cm) once the lack of roots at the sampling spots was confirmed. Next, the 6 × 6 × 2 cm samples were inserted side by side and carefully pressed until fully inserted into the soil. The samplers were gently removed from the soil after being inserted using a narrow-bladed spatula by making small excavations on the sides and underneath the sample to preserve the integrity of the soil structure.

2.2 Testing Methodology

2.2.1 Field Moisture Content

The moisture content of the samples collected from the location was assessed in accordance with the applicable standards, IS 2720 (part 2)-1973, and the findings are presented in Table 3.

2.2.2 Specific Gravity

For various geotechnical purposes, the determination of specific gravity is commonly required when analysing soil. The specific gravity was assessed following the guidelines outlined in IS: 2720 (part 3) (B. of Indian Standards IS 2720-3-1, 1980), utilising a density bottle. The obtained results are presented in Table 3.

2.2.3 Liquid Limit Test

The Atterberg limits were established for air-dried samples that passed through a 0.425 mm sieve, employing the wet-to-dry procedure and Casagrande cup method in accordance with IS:2720-part 5 (B. of Indian Standards IS 2720-5, 1985). Similarly, the plastic limit values were acquired following IS: 2720 part 5 (B. of Indian Standards IS 2720-5, 1985), and the corresponding results are found in Table 3.

2.2.4 Proctor Compaction Test

Table 3 presents the results of the standard Proctor compaction test based on the Indian standard IS 2720-part 7(B. of Indian Standards IS 2720-7, 1980), which determined the optimum moisture content (OMC) and maximum dry unit weight (MDU) of the soil.

2.2.5 Strength Characteristics

Soil strength parameters play a crucial role in determining the stability and bearing capacity of soil. In this current study, two types of strength analysis were conducted: unconfined compressive strength (UCS) and shear strength. The properties were evaluated using the unconfined compression test (UCT) and direct shear test (DST), respectively, following the standards IS: 2720-part 10 (B. of Indian Standards IS 2720-10, 1991) for UCT and IS: 2720-part 39 for DST (B. of Indian Standards IS 2720-39-1, 1977). The results of these tests are presented in Table 2. For the direct shear test, 6*6*2 cm samples were prepared in the laboratory and packed fast in a shear press by applying normal and horizontal forces (IS 2720) (B. of Indian Standards IS 2720-39-1, 1977). In this study, normal stresses (50, 100, 150 kPa) were applied to specimens according to information found in the literature (Ferreira et al., 2022). According to the Indian Standard of Slope Stability (IS 2720), shear tests were conducted for each of the normal stresses. Thus, each resistance envelope was built on silty clay soil, with and without roots. A root area was measured after direct shear tests. After dividing the samples in half, each root diameter crossing the failure surface was measured (Gray et al., 1996) to determine a relationship between soil area and root area (Ar/As) by determining the average root rate per soil area (%) (Fig. 2). Granulometric tests and physical index calculations were carried out for soil characterisation, using (Cardoza et al., 2020) as a guide. These calculations included saturation degree (S), porosity, void ratio (e), apparent specific natural weight (n), actual specific grain weight (s), and apparent specific dry weight (d). Using the MS Excel programme, all data gathered from field surveys and lab analyses were combined and examined Table 3.

2.3 Particle Size Distribution

Particle size analysis, also referred to as mechanical analysis, involves determining the proportions of different sizes of primary soil particles. This is typically done by either measuring their ability to pass through sieves of varying mesh sizes or observing their settling rates in water. These proportions are commonly represented by the relative weight of particles within specified size classes. The results are then used to create a particle size distribution curve, as depicted in Fig. 3.

Table 2 Untreated soil properties (Source: Its author)

Soil properties	Values	Soil properties	Values
Gravel (%)	0	Specific gravity, G	2.50
Sand (%)	0.6	Liquid limit (%)	64.70
Clay (%)	14	Plastic limit (%)	41.80
Silt (%)	85.4	Plasticity index (%)	23
D_{10} (mm)	0	Liquidity index	0.20
D_{30} (mm)	0.0044	PI (A-line) (%)	32.70
D_{60} (mm)	0.014	PI (U-line) (%)	51
Field water content (%)	46.30	Soil classification	MH
Field bulk density (kN/m^3)	17.1	Clay mineral type	Kaolinite
q_u (kN/m^2)	19.1	Free swell index (%)	11.40
c_u (kN/m^2)	8.50	Compression index, c_c	0.38
Angle of internal friction (φ)	23.94	Cohesion, c (kN/m^2) (DST)	6.52

(a). Sheared soil sample failure with the application of root

(b). The application of vetiver grass root in areas prone to landslides along roads.

Fig. 2 **a** Sheared soil sample failure with the application of root. **b** The application of vetiver grass root in areas prone to landslides along roads

Table 3 Testing program

S. no.	Description of test	Root length (mm)	Root content (%)	No. of tests
1	Compaction	20–25	0, 0.5, 1.0, 1.5, 2.0, 2.0	6
2	UCS	20–25	0, 0.5, 1.0, 1.5, 2.0, 2.0	6
3	DST	20–25	0, 0.5, 1.0, 1.5, 2.0, 2.0	24
Total tests				36

3 Results and Discussion

In this study, the compaction and shear strength characteristics/parameters have been discussed. The effects of locally available root fibre on their parameters have been presented separately in the section below:

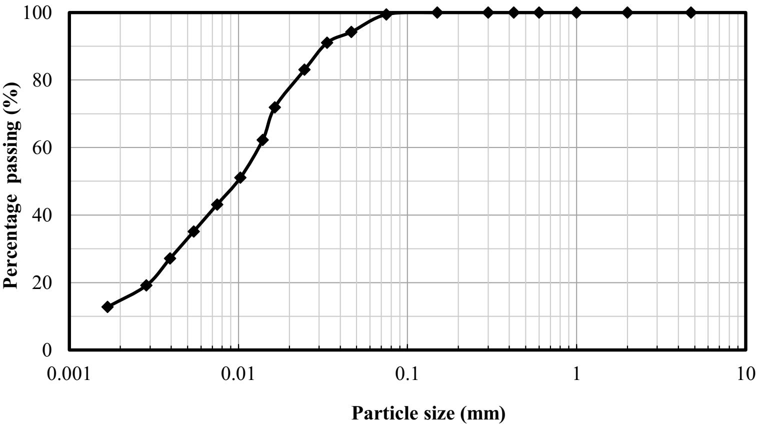


Fig. 3 Particle size distribution curve

3.1 Compaction behaviour
3.2 Shear strength
3.3 Direct shear test
3.4 Unconfined compression tests

3.1 Proctor Compaction Test

The standard proctor compaction test, following the Indian standard, IS: 2720 (part 7) (Indian Standard Methods of test for Soils Part 8, 1984), was utilised to determine the OMC and MDU of the soil. By plotting the dry density against the water content, the OMC and MDU values were identified and depicted in Fig. 4. Specifically, the

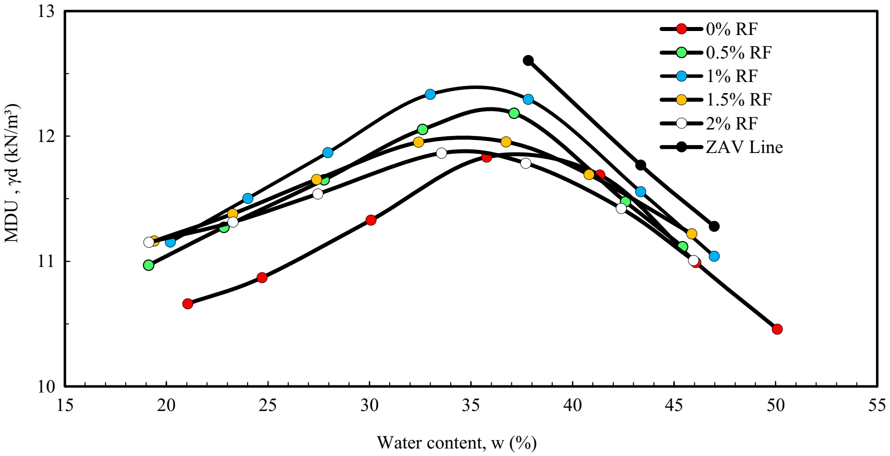


Fig. 4 Variation in compaction characteristics of soil with root content

soil OMC and MDU were found to be 36% and 11.8 kN/m^3, respectively (Table 4). The compaction curve representing this data is shown in Fig. 4.

3.2 Effects of Compaction on the Root

Soil compaction can negatively affect crop growth and production, both directly and indirectly, by promoting soil erosion and runoff. Researchers (Donn et al., 2014) have attempted to model virgin compression curves using an equation considering water content; however, obtaining such data is not always easy or feasible. While there are limited studies on the impact of roots on soil compaction characteristics, a recent investigation revealed a noteworthy finding. The compaction curve diagram indicated that the maximum dry density (MDD) decreases as the root fibre content increases. This is likely due to the lower specific gravity of root fibres, which leads to the formation of a unique soil network when added to the soil. As previously noted, the incorporation of roots in both sandy and clayey soils leads to higher shear strength in the test 402 specimens primarily due to increased cohesion (Gul & Mir, 2022; Gul et al., 2023).

The interaction of fibres with soil involves both adhesion and friction, contributing to soil stability and preventing failure under loading. Moreover, the addition of fibres makes the soil ductile and able to withstand stresses without undergoing damage, allowing engineers to take timely measures to protect structures. The strength mobilised by friction at the fibre-soil interface depends on the length of the fibres immersed in the soil. As the soil matrix fills voids when root fibres are introduced, the MDD value increases. However, when the root fibre content exceeds 1% in the soil, the MDD value starts to decrease, likely due to excess fibres causing segregation in the soil matrix and reducing its density. The compaction test results indicate that the soil density increases while the optimum moisture content decreases. This phenomenon occurs because the root fibre contents can fill the voids within the soil, but beyond the optimum water content, the soil loses its capacity to fill these voids. Consequently, the optimum moisture content decreases after this point.

3.3 Direct Shear Test

Direct shear tests were carried out on soil samples, both untreated and treated with RF (reinforcing fibres) (Figs. 15 and 16). Graphs depicting the relationship between

Table 4 Variation of root with different OMC and MDD

S. no.	Root	OMC	MDD	% Change in OMC	% Change in MDD
1	0	35.000	11.78	0	4
2	0.5	37.000	12.15	6	4
3	1	38.000	12.4	9	6
4	1.5	36.000	11.95	3	2
5	2	35.000	11.71	0	-1

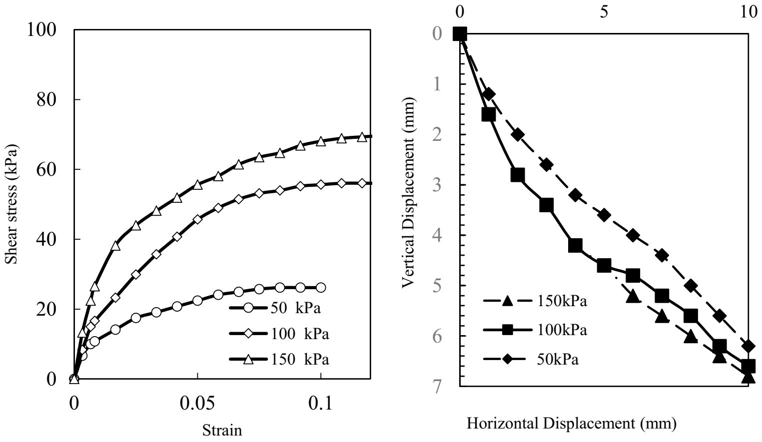


Fig. 5 Results of direct shear tests with and without roots in silty clay showing how shear stress is related to horizontal displacement and vertical displacement (DST 0%)

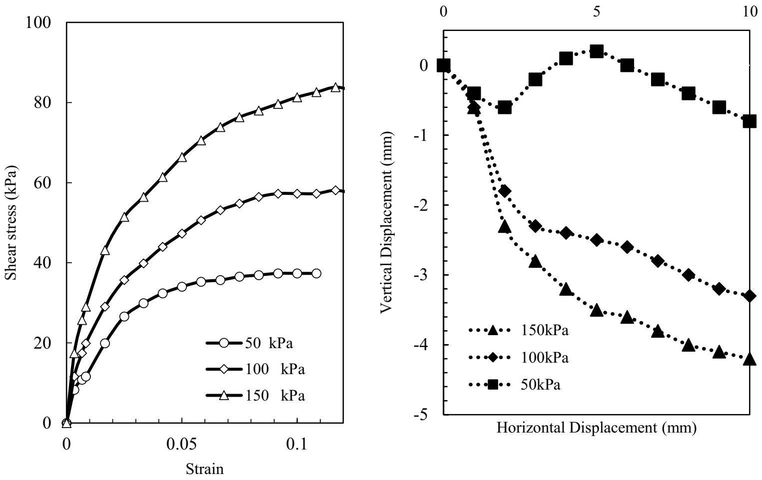


Fig. 6 Results of direct shear tests with and without roots in silty clay showing how shear stress is related to horizontal displacement and vertical displacement (DST 0.5%)

shear stress and strain were generated to determine the failure shear stress, as illustrated in Figs. 5, 6, 7, and 8. The graphical representations were created by plotting shear stress against normal stress to compute the parameters of direct shear testing, namely, cohesion and angle of internal friction. Subsequently, the parameters were derived from these graphs, as depicted in Figs. 5, 6, 7, 8, 9, and 10.

In this study, the strength characteristics were determined by implementing the direct shear test, utilising soil samples with a maximum size of 4.75 mm. The cohesion and angle of internal friction parameters of the treated marginal soil are outlined in Table 2.

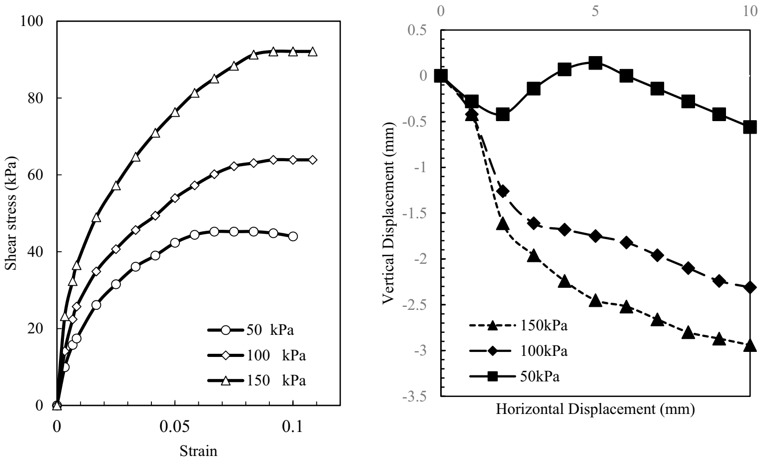


Fig. 7 Results of direct shear tests with and without roots in silty clay, showing how shear stress is related to horizontal displacement and vertical displacement (DST 1%)

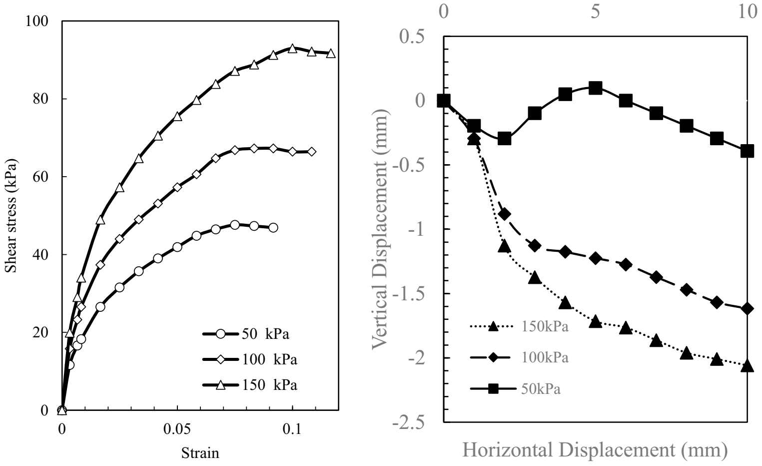


Fig. 8 Results of direct shear tests with and without roots in silty clay showing how shear stress is related to horizontal displacement and vertical displacement (DST 1.5%)

3.4 Percentage Change in Cohesion and Angle of Internal Friction

The results of the test conducted on soil stabilised grass roots that were locally available will be discussed in this. At 2%, cohesion is 29.32 kPa and the increase is 84%, as well as a marginal increase in angle of internal friction and an improvement in shear strength by 11% (Table 5). Grass roots were found to have a shear strength that increased by 3% (Maffra et al., 2019) found the same.

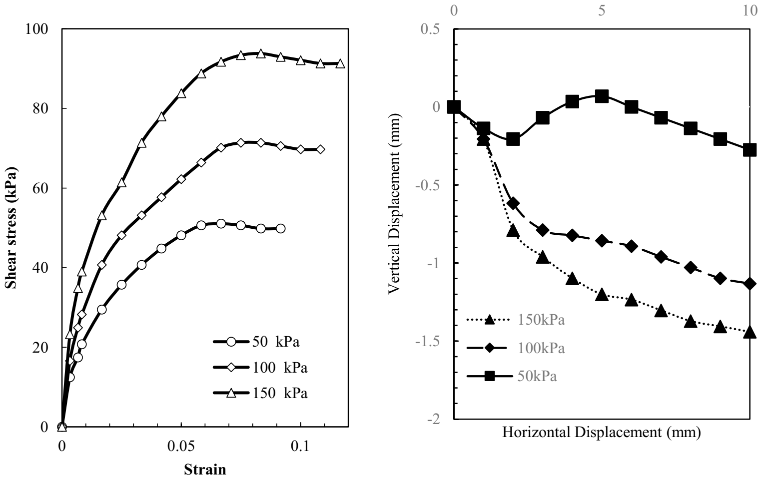


Fig. 9 Results of direct shear tests with and without roots in silty clay showing how shear stress is related to horizontal displacement and vertical displacement (DST 2%)

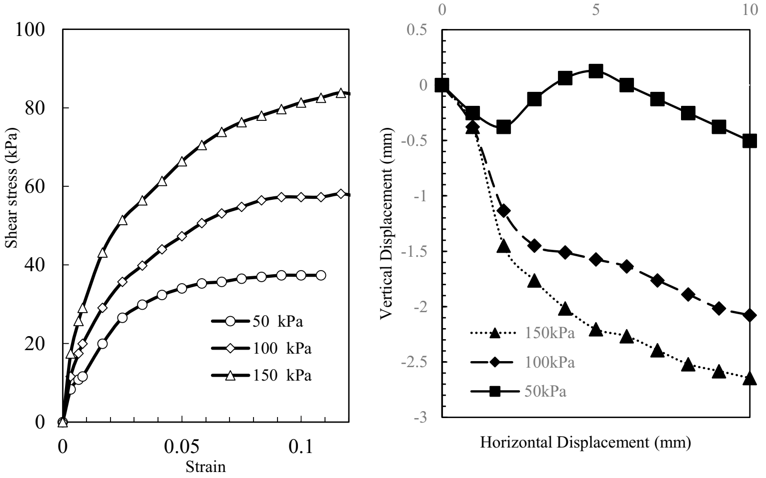


Fig. 10 Results of direct shear tests with and without roots in silty clay showing how shear stress is related to horizontal displacement and vertical displacement (DST 2.5%)

Figures 8, 9, and 10 indicate that fibre reinforcement inhibits dilatancy, particularly at high normal stresses. Previously conducted research in direct shear tests and triaxial tests (Mickovski et al., 2005) supports this finding. Other researchers have found, however (Anagnostopoulos et al., 2014), that fibres consistently increase the tendency of fibre-reinforced samples to dilate, particularly when the fibre lengths are longer, which was the case for samples with 50 mm fibre lengths. Compared to published results, the main difference in this study is the soil relative density, which was taken to be 50% in this study, while it was always greater than 50% in all the

Table 5 Laboratory testing program

Sample	Fibre content (%)	Cohesion (Kpa) c=	Angle of internal friction ϕ	%age Improvement of cohesion c =	Improvement of shear strength parameter %
Virgin soil	0.0	6.501	23.94	0	0
RFS	0.5	14.94	24.1701	120	1
RFS	1.0	19.64	25.314	72	6
RFS	1.5	23.90	26.370	65	11
RFS	2.0	29.32	24.130	84	1
RFS	2.5	21.85	23.92	−110	1

previous studies, as well as the size of the shear box (scale effect), which may have contributed to the observed discrepancies as direct shear test results are known to be sensitive to soil specimen size.

3.5 Effect of Roots on Shear Strength Parameters

A comparison between failure envelopes shows that soil samples with roots have a higher angular coefficient (angle of internal friction) and cohesion value (cohesion intercept). A soil without roots had an average cohesion value of 6.51 kPa, while a soil with roots had an average cohesion value of 23.94 kPa. There is a difference of 22.50 kPa between these two values. Essentially, roots increased the shear strength of the soil by 234% as a result of their presence in the soil. Soil without roots had an average angle of internal friction of 23.94°, while soil with roots had an average of 25.31°. There is a difference of 1.37° between the two values. This indicates, in relative terms, that the angle of internal friction created by the roots allowed the shear strength to grow by 6.4%.

The values of the silty clay soil strength parameters mirrored the pattern noted in the literature, indicating that rises in the cohesive intercept are the primary cause of shear strength enhancement (Graf & Frei, 2013).

This outcome has been explained by the modest inherent cohesion of the granular soils. When the soil has a high moisture content, the roots have a propensity to help contribute a greater amount to the shear strength from the perspective of mechanical reinforcement (Tengbeh, 1993). The roots caused a slight alteration in the angle of internal friction of the soil. Studies have shown that roots often cause small soil particle rearrangements (Wu et al., 1988). This might be related to the minimal number of roots that are often present on the weakened surface. The RAR, which measures the average root rate per unit area of soil, has typically been less than 1% (Helliwell et al., 2019).

This ratio appears to explain why the angle of internal friction is not significantly affected by changes in the particle arrangement of a soil block with few roots. On the contrary, the findings showed that cohesiveness was significantly impacted by the failure surface modest average fraction of roots. This has to do with how the roots are affected by the silty clayey soil. This sort of soil often has relatively little internal cohesion, but it benefits greatly by the friction between the particles. The roots often provide a physical barrier between soil particles on the failure surface. If the friction strength among soil and the section of roots that is immersed in the soil layers both above and below the failure surface overcomes their resistance, they could actually rupture the fibres. In this situation, roots frequently serve as natural rods (Gray et al., 1996), which promotes interaction among various soil layers The presence of the roots slows down soil deformation during the direct shear test through the highlighted mechanisms, which directly impacts the resistance peaks and, in turn, the cohesion increase.

3.6 Effect of the Roots on the Shear Strength Parameters with Different Percentages of Root

Overall, the results of this research align with the findings previously documented by (Watson et al., 1999), who investigated sandy-clay composites enhanced with propylene fibres. The previous study's authors observed that incorporating synthetic fibres, acting as root analogues, into the test samples significantly improved soil shear strength. These improvements were attributed to both increased cohesion and an elevation in the angle of internal friction within the soil-fibre mixture.

The presence of roots increased the shear strength of the test specimens in silty clay soils, primarily by increasing cohesion. These findings are in line with those of other researchers who have used plant roots as reinforcements (Greenwood, 2006) and natural fibres as reinforcement in terms of cohesiveness. It may be said that anytime roots cross the failure surface on the shear surface, the value of this parameter rises. When roots are subjected to a shear force, they may rupture or slip. As soil reinforcement elements, roots contribute more when they are resistant to these two failure modes. As a result, the deeper the roots are buried below a failure surface, the greater their ability to prevent movement in the upper soil layer since they add mechanical strength to the weaker layer (Kumar et al., 2020). Several roots can play a role in this, as well as their placement near the failure surface and/or their distribution there (Gray & Leiser, 1992). A random distribution of reinforcement is not usually applied, even in studies involving composite materials in which multiple fibre types are added to the soil to test their effects on shear strength. It appears that each soil type has an optimal fibre inclusion limit (Danjon et al., 2008).

As previously noted, the incorporation of roots in both sandy and clay soils led to higher shear strength in the test specimens, primarily due to increased cohesion. These findings align with observations made by various authors in different types of soils, including both granular and fine soils, where plant roots have been utilised as reinforcing elements (Watson et al., 1999).

3.7 Effects of Root on the Horizontal and Vertical Deformation of Silty Clay Soils

Experimental results showed that adding fibres to reinforced specimens with 20–25 mm fibre lengths reduced vertical displacements during shearing. A total of 2.0% fibre content reinforced specimens with 25 mm fibre length showed an increase

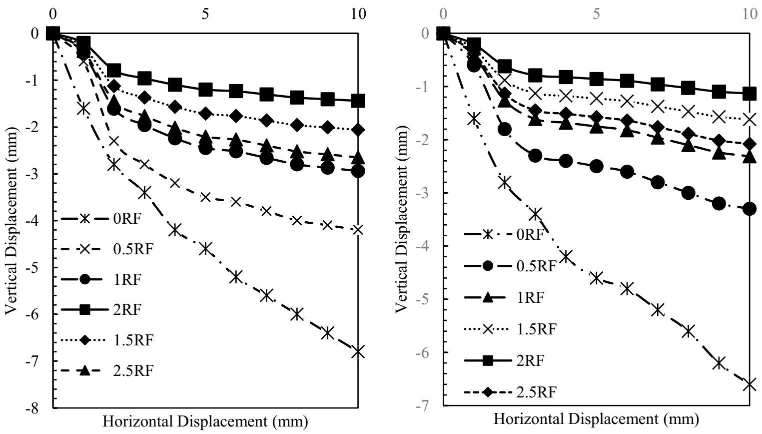


Fig. 11 Results of direct shear tests with and without roots in silty clay showing how shear stress is related to horizontal displacement and vertical displacement (150 kPa and 100 kPa)

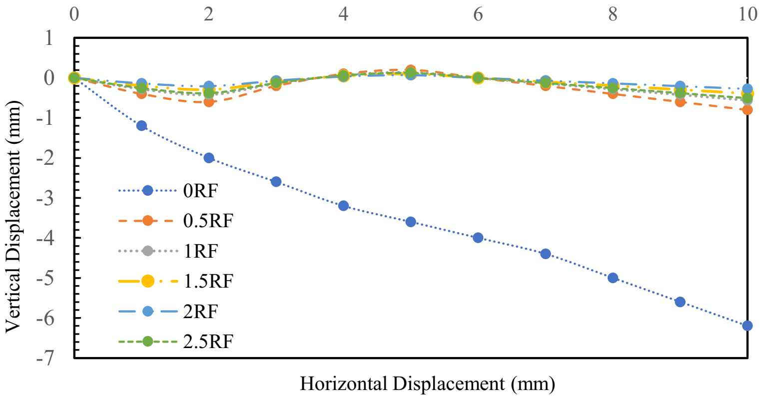


Fig. 12 Results of direct shear tests with and without roots in silty clay showing how shear stress is related to horizontal displacement and vertical displacement (50 kPa)

in vertical displacement with fibre content. Vertical displacement during shear is higher when fibres are present, suggesting a greater tendency for soil dilatation.

The volume change of the sample was verified by comparing vertical displacement to horizontal displacement during the direct shear test. According to the vertical displacement curves, soil specimens behaved similarly to unreinforced and fibre-reinforced samples. When the shear stress reaches a maximum, the samples vertical displacement decreases. Afterwards, vertical displacement becomes constant. A similar trend was observed for all samples at 50, 100, and 150 kPa normal stresses (Figs. 11 and 12). It was observed that fibre reinforcement decreased contraction behaviour for samples reinforced with 25-mm-long fibres, which indicates that the fibres merged the silty clayey soil particles and inhibited particle movement.

Under the three normal stresses applied during direct shear tests, roots had the highest values of shear stress (comparison between Figs. 8 and 9).

According to the results of the tests with roots, the specimens with roots exhibited an average resistance of 24.3 kPa higher than those without roots when considering the horizontal deformation. The specimens with roots exhibited greater resistance to deformation than those without roots when considering horizontal deformation as measured by the tests with roots.

There was also a positive influence of roots on vertical soil deformation. Figures 8 and 9 provide evidence of this. According to the results of the lower normal stress applied to the test specimens in Figs. 8 and 9, when the horizontal deformation is 100 kPa, the compression deformation increases with the horizontal deformation. However, in soil with roots, the compressive deformation increases. Roots promote the reorganisation of solid particles as they expand the shear zone beyond this value. By changing the direction in which the particle moves, the barrier effect is overcome since the least resistance direction is necessarily the one in which the particle moves. Vertical deformations are effectively controlled at normal stress levels up to 100 kPa when roots are present in the soil. The vertical deformations, however, increased significantly in soils with roots above 100 kPa. Although they remained lower than in soils without roots, they were still above what was presented in soils with roots

Figure 9 shows a horizontal compression test of soil with roots at 100 kPa, indicating that roots could rupture at the shear surface due to overcoming soil tensile strength or friction resistance (Jan et al., 2022). A horizontal deformation may cause particle rearrangement by modifying the soil area where roots have an effect (horizontal deformation).

It is important to note that the contrast between natural reinforcement (roots) and manufactured elements (which imitate roots) became significant. Due to the dearth of research on clay soil volumetric and horizontal deformation as well as the impact of the root systems of plants on shear strength, this was necessary. Due to their less complex structure and ease of isolating the effects of fibre inclusion, sandy soils are frequently used in these types of experiments.

3.8 Unconfined Compressive Strength

Unconfined compressive strength tests were carried out on both the untreated virgin soil sample and the same sample treated with varying percentages of root fibre (RF%) to evaluate the impact of the treatment on its strength. The soil sample underwent testing at different RF% levels, and graphs were generated to establish the relationship between axial stress and axial strain (%). This facilitated the determination of the critical stress, as depicted in Fig. 13. The figure illustrates the unconfined compressive strength of the untreated virgin soil alongside the same soil treated with different proportions of root fibre, including the corresponding undrained cohesion strength. Additionally, it offers a comparative analysis of how the unconfined compressive strength varies with changes in the root fibre percentage, showcasing the strength characteristics of the virgin soil at different RF% levels.

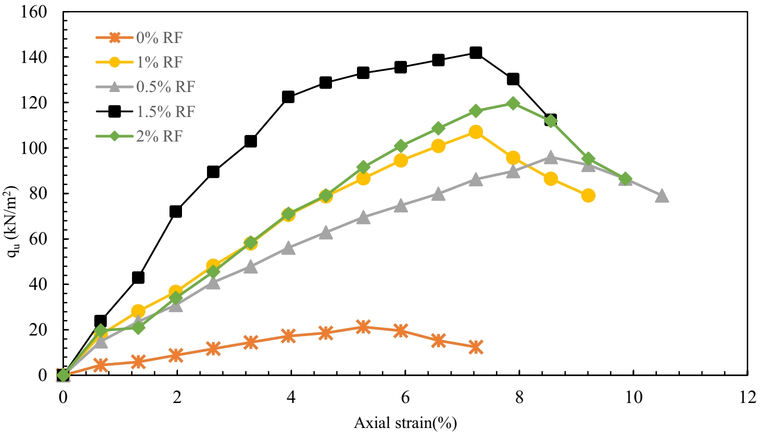


Fig. 13 Stress-strain curves for both reinforced and non-reinforced samples at different fibre percentages

3.9 Effects of Root on UCS of Soil

Unconfined compression tests, conducted following IS: 2720 (part 10) (B. of Indian Standards IS 2720-10, 1991), reveal the stress-strain behaviour of root fibre-reinforced soil, as depicted in Fig. 13. The incorporation of root fibres enhances the stress-strain behaviour, although their tensile strength remains lower than that of the soil. Nonetheless, the reinforced soil exhibits increased ductility and peak stress as the fibre content rises. Figure 13 illustrates how unconfined shear strength varies at different fibre percentages, with higher fibre content leading to an increase in UCS, peaking at 1.5%. Studies (Morgan & Rickson, 1995; Muir et al., 2016) show that the fibre content also increases linearly over time. Mixing root fibres with soil increases the shear strength of the soil (Morgan & Rickson, 1995). Unreinforced and reinforced soils exhibit significantly different UCC strengths, with the reinforced soil blends having a higher UCC strength than unreinforced clay. For instance, the (Hamidifar et al., 2018) addition of 1.5% fibres by weight results in an unconfined compressive strength twice that of unreinforced soil, indicating improved ductility observed in the stress-strain curve. Furthermore, root fibres have shown potential to enhance soil cohesiveness. Another study (Ghestem et al., 2011) explored the influence of root fibre characteristics on stress-strain behaviour. The UCS improvement index was employed to compare the strength behaviour of unreinforced and reinforced soil samples. The findings support that reinforced soil with fibres exhibits higher UCC strength than unreinforced clay. Adding 1.0 % fibres by weight leads to a twofold increase in unconfined compressive strength compared to unreinforced soil. These observations are consistent with an earlier study (Gul & Mir, 2022) that demonstrated an improvement in the ductility of soil-root composite according to the stress-strain curve.

3.10 Scanning Electron Microscopy (SEM)

SEM is a powerful tool used in various scientific fields, including soil science, to study the surface morphology and microstructure of materials. When studying soils induced with root fibres, SEM micrographs serve several important functions:

1. Visualisation of root-fibre interactions: SEM allows researchers to visualise the interactions between plant roots and soil particles or fibres at a high resolution. This can provide insights into how roots physically interact with the soil matrix, whether they penetrate the soil particles, wrap around them, or form networks.
2. Characterisation of soil structure: SEM micrographs help in characterising the soil structure induced by root fibres. Roots can create pore spaces, channels, and voids in the soil, affecting water infiltration, aeration, and nutrient movement. Understanding the soil structure is crucial for assessing its fertility, water-holding capacity, and overall health.
3. Quantification of root morphology: SEM images can be used to quantify root morphology, such as root diameter, length, branching patterns, and root hair development. This information is vital in understanding how root systems contribute to plant growth, nutrient uptake, and soil stabilisation.
4. Assessment of root-fibre attachment: SEM allows researchers to examine the attachment points between root fibres and soil particles. Understanding how roots anchor themselves in the soil can provide valuable knowledge for soil erosion control and stabilisation in different ecosystems.
5. Evaluation of soil compaction: Root fibres play a role in soil aggregation and can affect soil compaction. SEM can help visualise the effects of root fibres on soil compaction, which is important for agriculture, engineering, and environmental applications.
6. Identification of soil organic matter: In soils, root fibres may undergo decomposition and contribute to soil organic matter formation. SEM can be used to identify the decomposition stages of root fibres and the associated microbial activity.

The mechanical properties of materials are directly influenced by their microstructure. The microanalysis proves to be an invaluable approach to investigate these properties. Therefore, a comprehensive examination of the microstructure in the context of fibre-reinforced soil structures becomes highly significant. Figure 7 showcases notable voids, indicating loosely bound soil particles in the untreated soil. In contrast, the treated soil exhibits filled voids due to the presence of fibres. The interaction between the fibres and soil enhances the soil-fibre bond, leading to improved overall stability. To understand the underlying mechanisms thoroughly, it becomes essential to individually study the interaction of fibres with soil grains and the behaviour of the soil-fibre matrix. This approach allows us to uncover the intricate workings and effects of these elements. A soil-fibre column is created when soil particles with a size smaller than the fibre diameter ($D_{50} < D_f$) adhere to the surface of the fibre, forming soil-fibre columns.

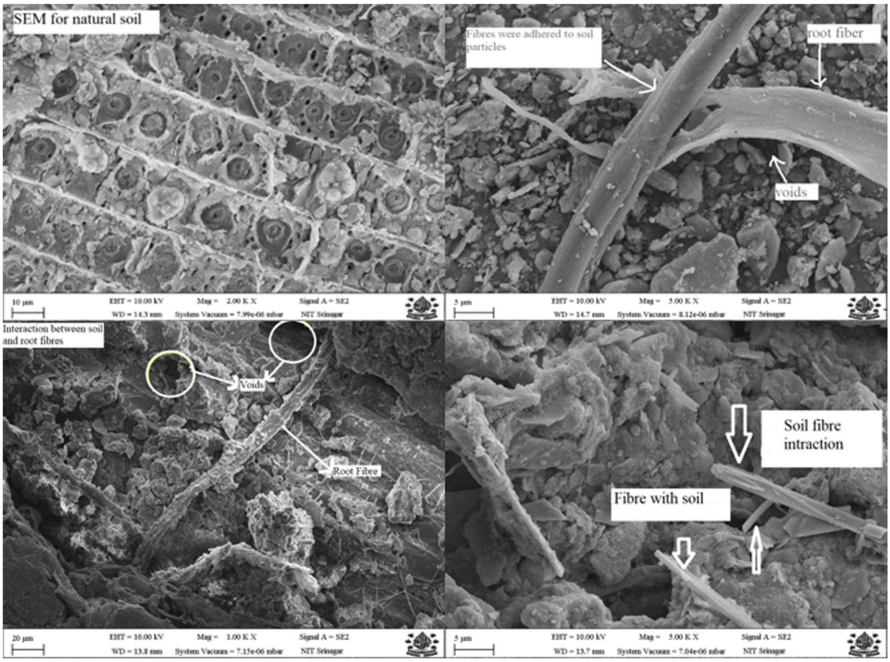


Fig. 14 SEM images depicting the interaction between soil and roots

Figure 14 illustrates that even after shearing, dirt particles remain attached to the fibre surface, confirming stress transmission within the soil-fibre column facilitated by the inherent strength of the soil and the mobilisation of the fibre tensile strength. The soil-fibre network develops as the concentration of fibres in the soil specimens increases, enabling stress transfer over a wider area. In some cases, soil particles adhere so strongly to the fibre surface that SEM micrographs reveal pits and grooves. An increase in fibre surface abrasion enhances fibre interfacial conditions due to particle impaction, leading to interlock resistance (Cazzuffi & Crippa, 2005). Despite these micromechanical interactions, the failure plane has no visible cracks. However, hairline cracks become apparent as the sample swells, indicating a transition from brittle to plastic behaviour Figs. 15 and 16.

4 Limitations of Bio-Engineering

Though bio-engineering has a number of advantages, it possesses some limitations also. Some of the limitations are given below:

1. Root characteristics can lead to misinterpretations in deep-seated failures as different vegetation species have varying root lengths, potentially resulting in large mass movements.

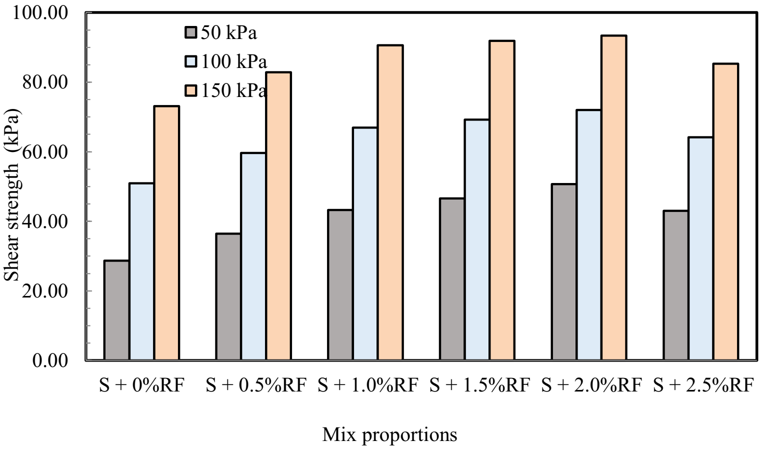


Fig. 15 Shear strength parameters at different kPa

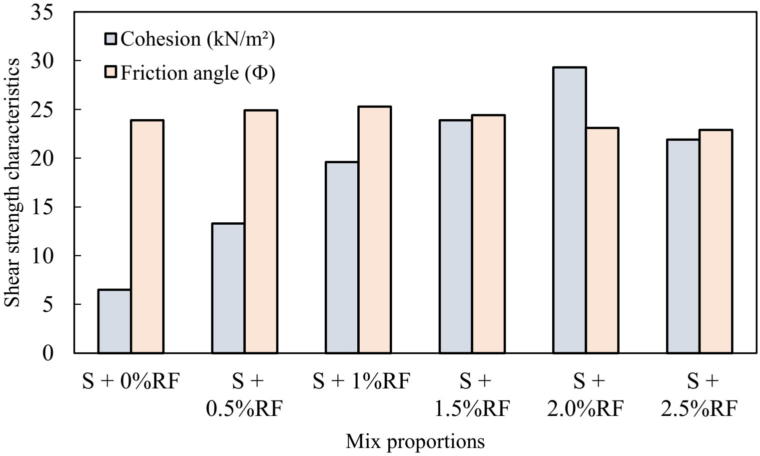


Fig. 16 Variation of shear strength parameters with root contents

2. Wind forces, though generally less significant than other factors, can still affect the stability of large trees and may disrupt transportation operations.
3. Large-diameter roots spreading over significant areas can adversely affect foundations, walls, embankments, and other structures.
4. Careful and season-specific planning is necessary for effective reinforcement with vegetative cover.
5. Designing for bio-engineering requires a high factor of safety due to the complex interactions between soil particles and roots.
6. The slow rate of reinforcement due to plant growth and increased soil surface roughness may hinder the functionality of bio-engineered slopes and soils.

7. The site-specific nature of bio-engineering necessitates the selection of appropriate plant species based on factors such as climate and soil type, impacting project outcomes.
8. Consideration of roots penetrating cracks in rock masses is essential to avoid exacerbating openings during bio-engineering projects.

5 Recommendations for Future Research Work

- Investigation of complex root-soil interaction: Further advanced research is needed to understand the complex interactions between roots and soil. This will help in developing more accurate and long-lasting designs for bio-engineered soils and slopes.
- Evaluate root properties: Accurate evaluation of root properties, such as root type, length, and density, is crucial for successful bio-engineering projects. Future studies should focus on developing reliable methods to measure and analyse these properties.
- Soil type consideration: The influence of soil type on the effectiveness of bio-engineered solutions should be thoroughly studied. Different soil types may require specific vegetation species and root characteristics for optimal reinforcement.
- Advancements in monitoring techniques: Research efforts should be directed towards improving monitoring techniques for bio-engineered slopes and soils. Real-time data collection and analysis can help assess the performance and long-term behaviour of these systems.
- Long-term performance assessment: Conducting long-term studies on bio-engineering projects will provide valuable insights into the durability and effectiveness of vegetative covers in reinforcing soils. This will help in identifying any potential challenges and improving the overall performance.
- Comparative studies: Comparative studies between different bio-engineering techniques and traditional engineering methods can help identify the strengths and limitations of each approach. This will aid in making informed decisions when selecting suitable stabilisation methods.
- Root-rock interaction: Further exploration of the interaction between roots and rock masses is essential, especially in areas with geological challenges. Understanding how roots affect rock stability can enhance the safety and reliability of bio-engineered solutions.
- Modelling and simulation: Developing advanced numerical models and simulations can assist in predicting the behaviour of bio-engineered slopes and soils under various conditions. This will facilitate better design optimisation and risk assessment.
- Environmental impact assessment: Comprehensive environmental impact assessments should be conducted to understand the ecological effects of bio-engineering projects. This includes studying the influence of vegetation on biodiversity, water resources, and other ecological aspects.

- Collaboration between disciplines: Encouraging interdisciplinary collaboration between soil scientists, geotechnical engineers, ecologists, and other relevant fields will foster innovative solutions and holistic approaches to bio-engineering challenges.

6 Conclusions

- This study highlights the potential of bio-engineering techniques to replace existing soil reinforcement methods. The results are encouraging for practising engineers to use the vetiver grass roots to improve the behaviour of low strength and marginal soil.
- Both direct shear and unconfined shear strength tests were conducted to explore the effect of root on the behaviour of reinforced soil.
- The results also demonstrated that roots have the capacity to absorb some of the water initially, leading to increased values of optimum moisture content (OMC). However, at higher root content, the OMC is found to decrease.
- The presence of roots resulted in enhanced shear strength for both sandy and clay soils. Shear strength improvement is found to be a function of root content, depth, weather conditions, and age. There is a significant enhancement in cohesion compared to the soil angle of the friction. Along with peak strength and residual strength, it also enhances with roots. It is important to highlight that the shear strength depends not only on root profiles but also on the physiological characteristics of the plants.
- Under low normal loads (50 kPa), almost all reinforced soil specimens show a marginal increase in shear strength. The shear strength improvement becomes more visible with fibre content and length at higher normal stresses, particularly for 25 mm fibres.
- In reinforced soil, the soil deformation was found to be minimised significantly, indicating the enhanced load-bearing capacity.
- The collected data provides analytical insights into the role of roots in soil reinforcement. This information could potentially contribute to the technical rationale supporting the utilisation of plants for erosion control and slope stabilisation purposes.
- Based on the obtained information, we can analyse how roots reinforce soils. Based on this information, plants or grass roots may be used to control erosion processes and stabilise slopes.

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Data Availability All data is available on request from the corresponding author.

Declarations

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

Competing Interests The authors declare no competing interests.

Conflict of Interest The authors declare no conflict of interest.

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