Soil Reinforcement and Slope Stabilization Using Natural Jute Fibres

R. Ramkrishnan[1(✉)], V. Karthik[2], M. R. Sruthy[3], and Animesh Sharma[4]

[1] Department of Civil Engineering, Amrita School of Engineering, Amrita Vishwa Vidyapeetham, Coimbatore, India
r_ramkrishnan@cb.amrita.edu
[2] Department of Civil and Environmental Engineering, University of California at Berkeley, Berkeley, CA 94720, USA
[3] Department of Civil Engineering, Faculty of Engineering and Technology, SRM University, SRM Nagar, Kattankulathur, Kancheepuram, Tamil Nadu 603203, India
[4] Afcons Infrastructure Ltd., Kolkata East West Metro, West Bengal 711103, India

Abstract. This study is aimed at determining the effectiveness of random inclusion of jute fibres on the strength characteristics of two different clayey soils. Fibre length and percentage inclusion in soil mass were taken as the initial study parameters. Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) tests were carried out to determine the strength parameters of the reinforced soil. Experimental results were then used to model the reinforced soil as embankment fills in finite element software programs PLAXIS 2D and SLIDE, to determine the safety factors. Results showed that the random distribution of jute fibres had positive effects on both strength parameters and the safety factors. The optimum fibre lengths and their respective percentage inclusions were then established. A mathematical expression, relating the UCS values to the fibre length and percentage inclusion was modelled from the experimental data using linear least square regression method in MATLAB. The data from the FEM software programs were compared with the mathematical expression, and it was observed that the expression held true for various strength parameter values, hence validating the expressions generated.

Keywords: Soil stabilization · Soil reinforcement · Natural fibers
Jute · FEM · Regression

1 Introduction

Soil stabilization can generally be termed as a process of improving the properties of natural soil by physical, chemical or biological means to meet the engineering requirement (Prabhakar et al. 2004; Binici et al. 2005; Sharma and Ramkrishnan 2016; Sahu et al. 2017). Use of fibres can basically be termed as a physical form of soil stabilization. Fibre-reinforced soil can be defined as a soil mass that contains randomly distributed, discrete elements, i.e. fibres. Fibres improve the mechanical behaviour of

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the soil composite. Tensile resistance in the fibres is mobilized by the normal stresses that act on the soil composite, which imparts greater shear strength to the soil. Most importantly, the behaviour of plant roots is replicated using random discrete flexible fibres, which adds strength to the soil mass and contributes to its stability. Artificial replication of the effect of vegetation has been proved by the usage of fibres for soil mass reinforcement by various laboratory and in situ pilot tests. Use of natural fibres for soil stabilization can be traced back to ancient construction works like Great Wall of China and Babylon (Hejazi et al. 2012; Kumar et al. 2015a, b). Although reinforcement of soil with natural fibres originated in ancient times, it can be concluded that fibre reinforced soil composites have recently gained widespread attention in construction projects. Today, with increasing urbanization and industrialization, the use of soil stabilization techniques is inevitable; hence a systematic study for optimization of the technique is necessary.

With that under consideration, the current study is based on the optimization of fibre reinforced soil stabilization. Of all the available natural fibres, jute fibres are preferred due to its good tensile properties and durability, making it apt for this study. The effect of varying the percentage of jute fibre and the length of the jute fibre was studied by Singh and Bagra (2013), and it was observed that increase in fibre length and percentage weight resulted in an increase in the CBR values. Bairagi et al. (2014) carried out a systematic study on parameters like UCS and CBR in jute fibre-reinforced black cotton soil. An appreciable increase in both the soil parameters was observed. Kumar et al. (2015a, b) studied the effect of the use of jute and coir fibres as soil reinforcement. The length of fibres and diameter of fibres were considered as varying parameters (20, 40, 60, 80 mm). From the results, it was concluded that with an increase in fibre content and fibre length, the CBR value further increased. Results also indicated that the diameter of the fibres also affects the reinforcing effect. Neeraja (2010), and Tapas and Baleshwar (2014), are other significant studies which observed similar results on jute fibre-reinforced soil.

Other natural fibres that have been used for soil reinforcement related studies include coir (Ravishankar and Raghavan 2004; Sivakumar Babu and Vasudevan 2008), palm (Marandi et al. 2008) and sisal (Prabakar and Sridhar 2002; Wu et al. 2014; Mathew and Raneesh 2016; Ramkrishnan et al. 2017). Earlier studies suggest that the degree of improvement of using soil natural fibres depends upon parameters like length of fibre, diameter of fibre and the percentage of fibres (by weight) to the soil mass (Ghavami et al. 1999; Bouhicha et al. 2005; Ahmad et al. 2010; Estabragh et al. 2011). Accordingly, length of the fibre and the percentage inclusion of jute fibres were the considered as varying parameters and their corresponding effects were observed and concluded accordingly.

The present study investigates the strength behaviour and slope stability of the soil reinforced with randomly included jute fibres. In order to understand the effect of inclusion of jute fibres on strength behaviour of clayey soil samples, a series of Unconfined Compressive Strength (UCS) tests and California Bearing Ratio (CBR) tests were conducted. The experimental results obtained from the laboratory tests were then further verified using a mathematical expression which related the strength parameters to the fibre length and percentage inclusion (Ranjan et al. 1996; Sivakumar Babu et al. 2008a, b). A mathematical expression for the reinforced soil strength performance was modelled from the experimental data using linear least square regression method in MATLAB. Furthermore, the practical implications of the use of natural jute fibres were ascertained using numerical modelling. Finite Element Software i.e. PLAXIS 2D and Limit Equilibrium Slope stability software i.e. SLIDE was used for numerical simulation of fibre reinforced slope embankments (Park and Tan 2005; Bhardwaj and Mandal 2006). The results from numerical analyses were then further compared with the mathematical expression, and it was observed that the expression was in good agreement with various strength parameter values.

2 Materials

2.1 Jute Fibres

Jute fibres were collected from Kolkata, (West Bengal, India). To maintain homogeneity of jute fibres properties, they were collected from a single batch of the production.

2.2 Soil Samples

Two soil samples, Soil-B and Soil-R, were collected from Palur and Thirukkazhakundram, Chengalpet (Tamil Nadu, India) respectively. Samples were collected from a depth of 1.5–2.0 metres from the ground level and its properties were tested according to Indian Standard (IS) specifications and are tabulated in Table 1. Both soil samples were classified as clayey soils or fine-grained soils.

Table 1. Properties of Unreinforced soil samples

Sl No.	Parameter		Symbol	Value	
				Soil-R	Soil-B
1	Grain size analysis	Sand	S	13.45%	40.55%
		Silt & clay	M&C	86.55%	59.45%
2	Specific gravity		G	2.25	2.24
3	Liquid limit		WL	51%	35%
4	Plastic limit		WP	19%	16%
5	Shrinkage limit		Ws	8%	13%
6	Plasticity Index		IP	32%	19%
7	Maximum dry density		MDD	15.9 kN/m^3	17.2 kN/m^3
8	Optimum moisture content		OMC	18%	17%
9	Unconfined compressive strength		UCS	171.7 kN/m^2	105.0 kN/m^2
10	California bearing ratio		CBR	6.20%	3.00%
11	Soil classification			CH	CI

3 Methodology

3.1 Experimental Procedure

Previous studies indicated that the shear strength increment was a function of the length of fibres used and the percentage inclusion of fibres. Accordingly, the fibres were cut into different lengths of 0.5 cm, 1 cm and 1.5 cm and were mixed with the soils at different percentage inclusion by soil weight (0.25, 0.5, 0.75, 1, and 1.25%) to reinforce them. The water content during sample preparation was the optimum moisture content of the respective soil type. For each fibre length, Unconfined Compression (UCC) tests were conducted according to IS 2720: Part-10, up to a percentage inclusion at which a drop in the Unconfined Compressive Strength (UCS) value was observed. Thus, the optimum percentage inclusion and fibre lengths in both the soils were established.

CBR tests were conducted on reinforced soil samples in accordance with IS 2720: Part-16. The tests were conducted on jute fibre-reinforced Soil R and Soil B, at optimum percentage inclusion for all fibre lengths (0.5 cm, 1 cm, 1.5 cm), and at optimum fibre length (1 cm) for all percentage inclusions (0.25, 0.5, 0.75, 1, and 1.25%).

3.2 Mathematical Regression

To arrive at a generalized equation that relates the UCS value of the reinforced soil to the fibre length and percentage inclusion, the experimental results were plotted as a 3-dimensional surface using MATLAB. The percentage inclusion and fibre length were chosen as the X and Y axes, while the UCS values were represented along the Z-axis. The variables were then plotted as a 3-dimensional surface using the curve fitting tool. The curves were fit as polynomials with percentage inclusion set to third degree and fibre length set to second degree. Weights were not assigned as both fibre length and percentage inclusion play an equal part in determining the strength improvement. The polynomial equation and the corresponding coefficients for both Soil-B and Soil-R were then obtained from the generated surface.

3.3 Numerical Analyses for Slope Stability

It was observed from the experimental results and mathematical analysis that random inclusion of jute fibres in fine-grained soils increased the strength of soil. In continuation of the analysis, a suitable implication of jute fibre reinforced soil can be high slope embankments which are widely used in the construction of highways, canals, and reservoirs nowadays. For the analyses, Finite Element Software i.e. PLAXIS 2D and Limit Equilibrium Slope Stability Software i.e. SLIDE was used. Slopes of varying heights (10 m, 15 m, 20 m, and 25 m) were simulated in these software programs to investigate the pattern of slope stability. For simplicity, 45° and 60° slopes were considered. In case of Finite element analysis, plane strain condition was considered, and the embankment mesh was kept as fine. In PLAXIS, phi-c reduction technique and for SLIDE, Bishops method was used to ascertain the factor of safety of slope embankments. The results from the experimental tests were used as parameters for numerical simulation of the slope embankments.

4 Results

4.1 UCS Test Results

4.1.1 Effect of Variation of Percentage Inclusion of Jute Fibre on UCS

The UCS variation of jute fibre reinforced Soil-R and Soil-B with the variation of percentage inclusions of jute fibre for each of the fibre lengths studied (0.5 cm, 1 cm, 1.5 cm) are discussed in this sub-head. The stress-strain curves of the UCS tests conducted in Soil-B and Soil-R for 0.5 cm, 1 cm and 1.5 cm fibres are shown in Fig. 1a, b respectively.

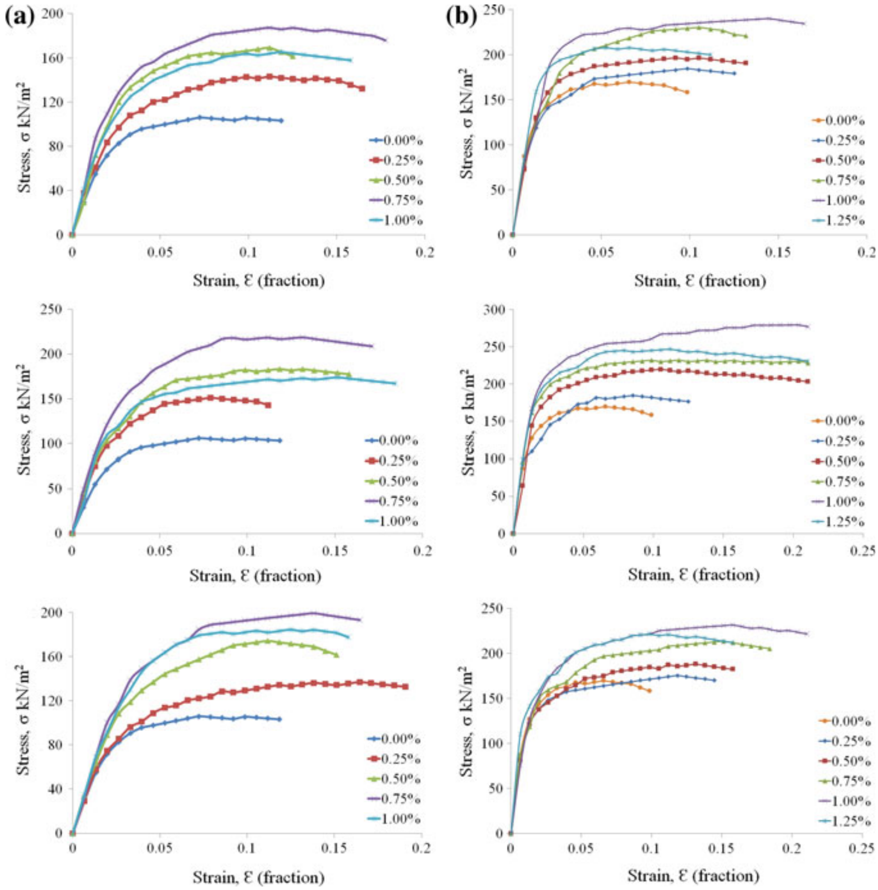

Fig. 1. Effect of varying fibre % on UCS of Jute reinforced (a) soil B and (b) soil R (0.5 cm, 1.0 cm and 1.5 cm)

The increase in percentage inclusion resulted in an increase in UCS irrespective of the fibre lengths used, up to a particular percentage inclusion after which the UCS started decreasing. The percentage inclusion corresponding to maximum UCS was established as the optimum percentage inclusion and its value was 1% in Soil-R and 0.75% in Soil-B for all the fibre lengths.

Soil-R and Soil-B had unreinforced UCS values of 171.7 kN/m^2 and 105.0 kN/m^2 respectively. The addition of 1% of 0.5 cm, 1 cm and 1.5 cm fibres increased the strength of Soil-R by 1.38, 1.55 and 1.32 times respectively whereas the strength of Soil-B was increased by 1.78, 1.93 and 1.87 times on addition of 0.75% of each fibre lengths. These observations confirm that jute fibre was more effective in reinforcing Soil-B than Soil-R. The same can be observed in the Fig. 2, which shows the variation of UCS with percentage inclusion for various lengths of jute fibres in Soil-R and Soil-B. The photographs of tested samples are shown in Fig. 3a, b respectively.

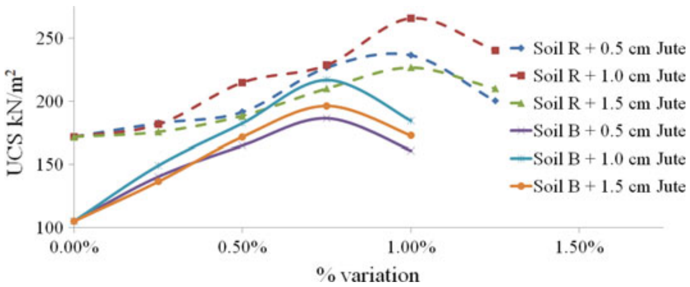

Fig. 2. Variation of UCS with percentage inclusion for various lengths of Jute fibres in Soil-R and Soil-B

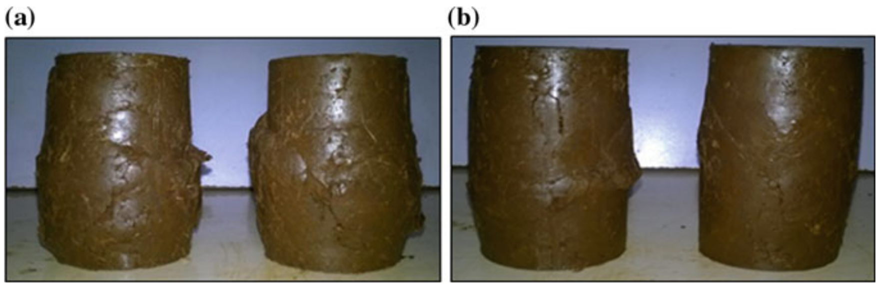

Fig. 3. UCC test samples of (a) Soil R at 1.0% Jute fibre inclusion and, (b) Soil B at 0.75% Jute fibre inclusion

4.1.2 Effect of Variation of Jute Fibre Length on UCS

The UCS variation of jute fibre reinforced Soil-R and Soil-B with the variation of fibre length for all the percentage inclusions are shown in Fig. 4.

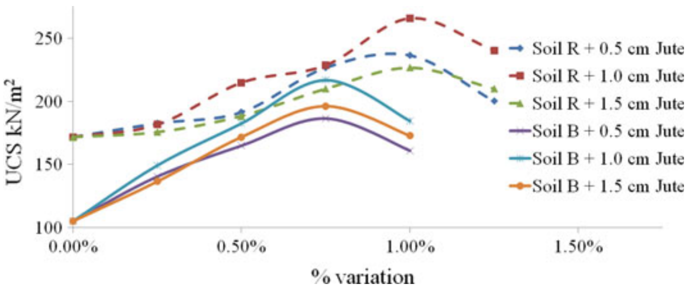

Fig. 4. Effect of Jute fibre length on the UCS of soil

It was found that 1.0 cm fibres, irrespective of the soil type, gave the highest UCS values. Fibres longer than 1.0 cm and higher percentage inclusions caused difficulty in mixing, due to bundling effect. So, the optimum jute fibre length was established as 1 cm for both the soils.

4.2 CBR Test Results

From the CBR tests, it was observed that 1 cm long fibres gave the highest CBR values, irrespective of the soil type or percentage addition. The CBR variation with fibres of various lengths and percentage inclusions are discussed below.

4.2.1 Effect of Jute Fibre Inclusion at Optimum Length on CBR of Soil

Jute fibres of length 1.0 cm were added to the soil samples at varying percentages from 0.25% to 1.25%, with 0.25% increments. The graphs showing the load-penetration curves of the CBR tests conducted in Soil-R and Soil-B are shown in Fig. 5a, b respectively.

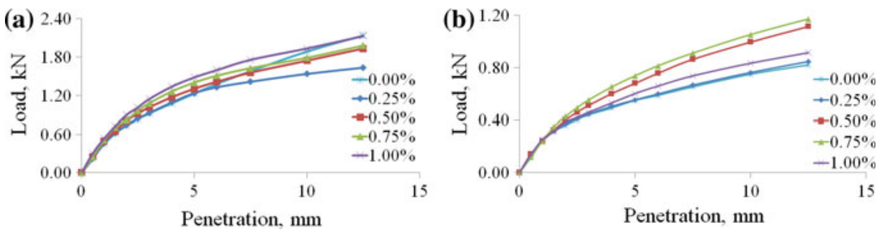

Fig. 5. Effect of varying fibre percentage on CBR of 1.0 cm Jute reinforced (a) soil R and (b) soil B

The addition of 1.0 cm fibres showed a gradual increase in the CBR values till optimum percentage inclusion of 1% in Soil-R and 0.75% in Soil-B, after which the CBR value decreased. An optimum CBR value of 7.55% was obtained in Soil-R and 3.68% in Soil-B, improving it from unreinforced values of 6.2% and 3.0% respectively. An increase of penetration resistance by 1.22 times in Soil-R and 1.23 times in Soil-B was observed. The effect of jute fibre was almost similar in both the soil types.

4.2.2 Effect of Length of Jute Fibre in Soil at Optimum Percentage Inclusion

Jute fibres of varying lengths (0.5 cm, 1.0 cm, and 1.5 cm) were added to the soil samples at optimum percentage addition of 1.0% in Soil-R and at 0.75% in Soil-B. The graphs showing the load-penetration curves of the CBR tests conducted in Soil-R and Soil-B are shown in Fig. 6a, b respectively.

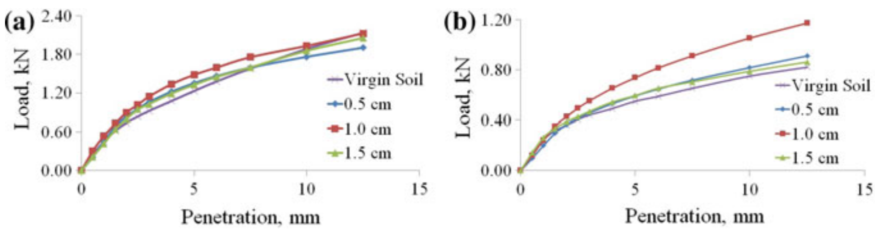

Fig. 6. Effect of varying Jute fibre lengths on CBR of (a) soil R and (b) soil B at optimum percentage inclusion

Fibre lengths of 1.0 cm were found to give higher penetration resistance when compared to 0.5 cm and 1.5 cm fibres at the optimum percentage inclusion. It was observed that at a fibre length of 1 cm (optimum), the CBR value increased with increase in percentage inclusion up to 1% in Soil-R and up to 0.75% in Soil-B, after which it started reducing. CBR variation followed almost the same trend as that of UCS variation. It was also observed that at a percentage inclusion of 1% in Soil-R and 0.75% in Soil-B, the CBR value increased with increase in fibre length up to 1 cm in Soil-R and Soil-B, after which it started reducing. Soil B and Soil R showed a similar pattern in the improvement of penetration resistance which can be easily observed from Fig. 7a, b.

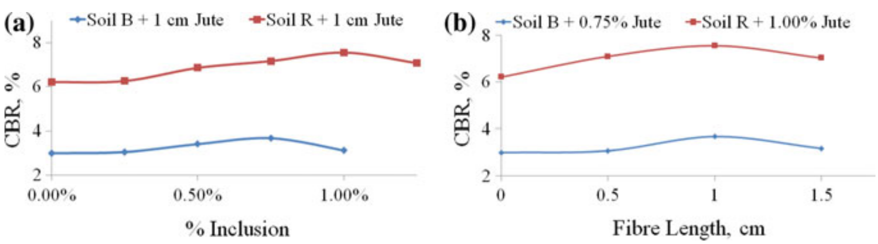

Fig. 7. Comparison of CBR variation with (a) varying percentage inclusion of 1.0 cm Jute fibre (b) varying jute fibre length at optimum inclusion

4.3 Mathematical Modelling Using MATLAB

The UCS values obtained for both Soil-R and Soil-B were used to obtain a mathematical expression relating the UCS values with the fibre length and percentage inclusion using MATLAB. Linear least squares regression method was used to obtain a 3-dimensional surface by plotting the experimental values for Soil-R and Soil-B, as shown in Fig. 8a, b respectively. The above-obtained curves resulted in a sum squared error (SSE) of 332.63 for Soil-R and 92.79 for Soil-B, while the R-square values were 0.9641 for Soil-R and 0.9823 for Soil-B. The polynomial equations of the surfaces for Soil-R and Soil-B are given below in Eqs. (1) and (2) respectively.

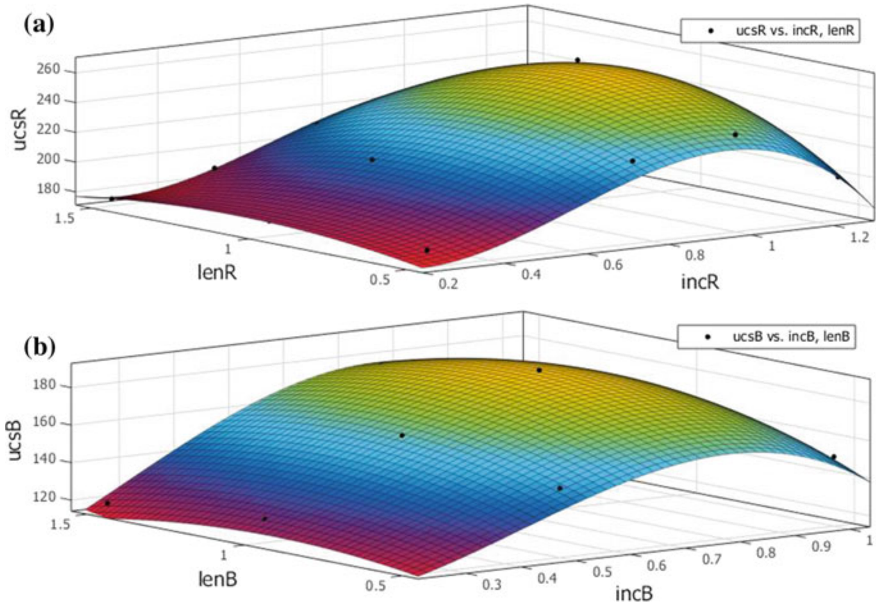

Fig. 8. 3-dimensional surfaces obtained for the mathematical expressions from MATLAB

$$q_u = 171.7 - 174.5p + 39.49l + 419.3p^2 + 112.8pl - 10.35l^2 - 264.6p^3 + 69.91p^2l - 104.3pl^2 \tag{1}$$

$$q_u = 105.0 - 96.60p + 14.00l + 344.7p^2 + 196.8pl - 18.37l^2 - 257.8p^3 - 70.57p^2l - 48.81pl^2 \tag{2}$$

where q_u represents the unconfined compression strength (kN/m^2), p represents the percentage inclusion of fibres (%) and l represents the fibre length (cm).

Table 2 shows a comparison between the experimental values and the UCS values obtained from the equations. It can be observed from the table that the values obtained from the equations are similar to the experimental values, with minimal variations. This validates the mathematical equations for the given data set. The size of the experimental data set and the number of soil types used for testing limit the possibility of obtaining a generalised equation for the UCS value of any type of soil that is fibre reinforced with jute fibres. The generalised equation can be attained by conducting the

UCC test on a large number of soil samples which have varying characteristics. Soils under the same classification can be grouped together to obtain a classification specific equation, which would be more relatable than having a single governing equation for all soil characteristics.

Table 2. Comparison of experimental and mathematical UCS values

Percentage inclusion p (%)	Fibre Length l (cm)	Experimental UCS values (kN/m^2)		Mathematical UCS values (kN/m^2)		Percentage variation (%)	
		Soil-R	Soil-B	Soil-R	Soil-B	Soil-R	Soil-B
0.00	0.0	171.7	105.0	171.7	105.0	0.00	0
0.25	0.5	182.5	117.7	177.1	120.1	2.98	2.05
0.25	1.0	181.5	126.5	185.8	126.6	2.36	0.07
0.25	1.5	175.6	118.7	176.3	117.8	0.39	0.79
0.50	0.5	191.3	151.1	197.3	147.3	3.11	2.49
0.50	1.0	214.8	162.8	207.1	162.6	3.60	0.10
0.50	1.5	188.4	155.0	185.6	156.5	1.47	1.00
0.75	0.5	226.6	159.9	224.6	164.9	0.88	3.12
0.75	1.0	228.6	189.3	239.9	184.6	4.94	2.48
0.75	1.5	209.9	175.6	210.9	176.8	0.47	0.71
1.00	0.5	236.4	151.1	234.3	148.6	0.87	1.64
1.00	1.0	265.9	164.8	259.5	168.4	2.43	2.15
1.00	1.5	226.6	156.0	227.2	154.5	0.28	0.97
1.25	0.5	200.1	–	201.6	–	0.76	–
1.25	1.0	240.3	–	240.9	–	0.26	–
1.25	1.5	209.9	–	209.9	–	0.00	–

4.4 Numerical Modelling of Slope Embankments Using Jute Fibres

Figure 9 shows the variation in the FOS values calculated from PLAXIS and SLIDE for 45° slope. An increment ratio of 1.49 in the cohesion value of Soil-B resulted in an increment ratio of 1.23 and 1.47 in the FOS values of PLAXIS and SLIDE respectively. Similarly, for an increment ratio of 1.80 in the cohesion value of Soil-R, increment ratios of 1.70 and 1.62 was observed in the FOS values of PLAXIS and SLIDE respectively. The cohesion values were taken for the optimum length (1.0 cm) from the experimental results.

Synonymous to the UCS and CBR experimental results, the FOS value gradually increased with an increase in the percentage inclusion. It peaked at 0.75% inclusion for Soil-R and 1.00% for Soil-B, after which there is a decrease in the value. This confirms the optimum percentage inclusions obtained from the experimental results and validates the methodical comparisons between the embankment and the experimental results i.e., random inclusion of fibres in soil with proper compaction in successive lifts till the required height is reached. Also, the FOS value decreases with increase in the

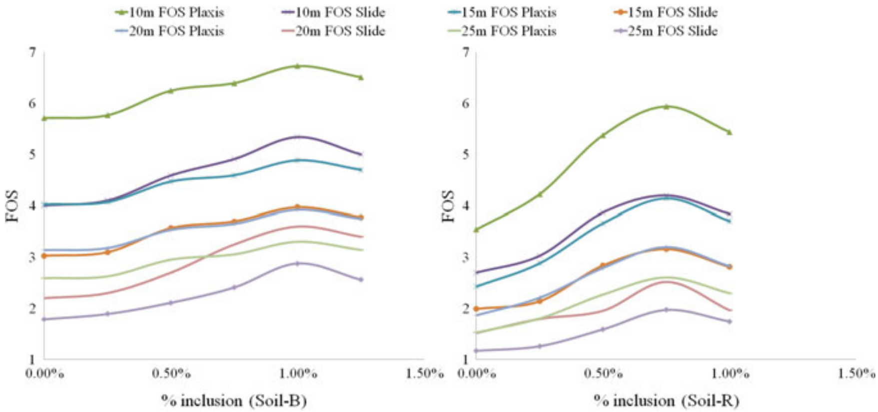

Fig. 9. Effect of varying percentage inclusion and embankment height on FOS of 45° slope

embankment height. This correlates to the fact that the stability of the slope decreases with increase in the slope height.

The variation in the FOS values for 60° slope is depicted in Fig. 10. An increment ratio of 1.49 in the cohesion value of Soil-B resulted in an increment ratio of 1.32 and 1.49 in the FOS values of PLAXIS and SLIDE respectively. Similarly, for an increment ratio of 1.80 in the cohesion value of Soil-R, increment ratios of 1.73 and 1.81 was observed in the FOS values of PLAXIS and SLIDE respectively.

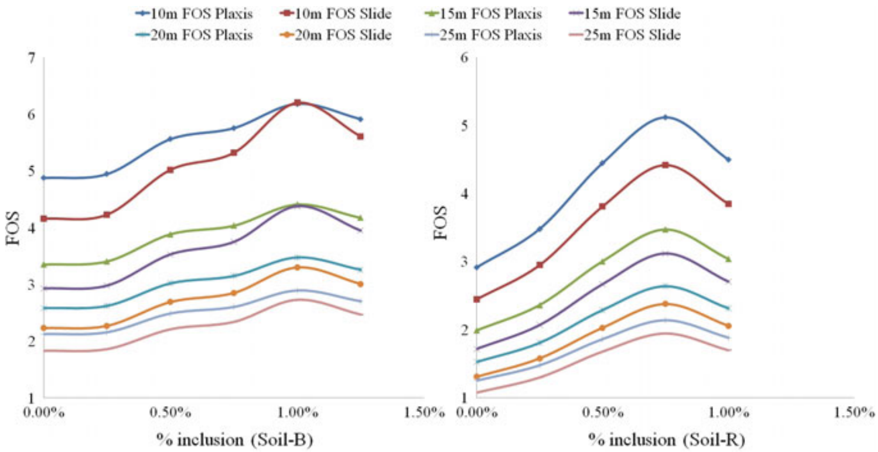

Fig. 10. Effect of varying percentage inclusion and embankment height on FOS for 60° slope

The above graphs and the increment ratios indicate that reinforced soil helps improve the FOS of steeper slopes considerably. It can also be concluded that in case of non-availability of required granular fill for construction of embankments, the available fine-grained soils can be reinforced with sisal fibres to attain a steeper, higher and relatively stable slope embankment. Adopting steeper slopes and reduction of the base width will also be possible using fibre-reinforced embankment fills, which reduces the quantity of material required and the costs involved.

5 Conclusion

An increase in the UCS and CBR values was observed with the addition of jute fibres to both Soil-R and Soil-B, with 1 cm fibre length for both soil types and 1.00% and 0.75% percentage inclusion for Soil-R and Soil-B respectively giving the highest values. Hence, they were reported as the optimum fibre length and optimum percentage inclusion respectively. The variation trends observed for both the soil types were similar as both the types were fine-grained soils with high clay content. The reduction in the shear strength for fibre inclusion beyond the optimum percentage can be attributed to the low specific gravity and low unit weight of jute fibres. The fibres fail to bond with the soil matrix effectively with further addition beyond the optimum values. CBR values of fibre-reinforced soil followed the same trend as that of UCS values and the highest value was observed for 1 cm fibre inclusion. The strength and stiffness of reinforced soil increased with the increase in fibre content which relates to the increase in the CBR value of reinforced soil.

The mathematical equations obtained gave UCS values similar to the experimental values. Hence, these equations can be used to determine the UCS values for various combinations of percentage inclusion and fibre lengths. A possible scope for research in this aspect could be the computation of a generalised equation to obtain the UCS values for various fibre lengths and percentage inclusions. This can be achieved by conducting tests on a large number of soil types with varying parameters. The variations in the basic soil parameters can also be taken into consideration while forming the equation to give more accuracy to the results.

The increment in the strength characteristics of soil indicates a possible application of fibres in the embankments for highway/road projects. Numerical analyses carried out to study the possibility of this application at the optimum fibre length resulted in an increase of the FOS of the embankment until the optimum percentage inclusion and a decrease beyond that. Hence, the stability of the slope increases when it is reinforced with fibres at an optimum percentage addition and length of the fibre. This allows for the economical usage of fibre-reinforced soils in embankments for highway/railway projects. Another practical advantage of using fibres as reinforcements for embankments will be that it will facilitate and accommodate vegetation on facings upon sowing. It will be a crucial aspect for the stability of slopes too, as it will prevent erosion.

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