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ORIGINAL ARTICLE

Utilization of alkali-treated areca fibers for stabilizing silty sand soil for use in pavement subgrades: Analysis using IITPAVE software

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Abstract

The increasing growth of urban areas and the rise in infrastructure development activities have put a strain on the availability of land with desirable soil conditions. This has led to the development of several stabilization techniques that can be used to improve the properties of weaker soils for construction. The research presented here explores the impact of inducing randomly oriented alkali-treated areca fibers for stabilization of silty sand soil. A sequence of experiments was carried out on the soil-fiber mixtures to investigate the strength of the soil after stabilization. At increments of 0.2%, the fiber dose varied between 0 – 0.8% of the dry weight of the soil. The tests conducted includes compaction tests, California bearing ratio (CBR), unconfined compression strength (UCS) tests, and unconsolidated undrained (UU) triaxial tests. The results obtained showed a notable increase in the strength of the soil-fiber mixtures. An increase in fiber content was found to increase the OMC (optimum moisture content) values and decrease the MDD (maximum dry unit weight) values. The maximum strength of the soil-fiber mixture was obtained at 0.6% fiber content. This makes it possible to use silty sand soil subgrades for low-volume roads with a traffic of less than 2 million standard axles based on the IITPAVE analysis. In essence, the test findings indicated that the ideal fiber content to be 0.6%. Stabilization of local on-site soils is one of the sustainable practices that can help extend the life of a pavement and lessen the need for more frequent repairs/maintenance.

Keywords Silty sand soil · Areca fiber · Stabilization · Sustainable design · Pavement subgrade · Shear strength · IITPAVE analysis

1 Introduction

The progress of a country's economy is dependent on its road infrastructure. Rural roads play a vital role in the economic development of a country, especially in developing economies [1]. Rural roads are treated as the last connections in the transportation network. Rural roads have the coveted distinction of providing access to socio-economic services [2].

The subgrade is an important layer of the pavement structure and it plays a vital role in the design, construction, and durability of the pavement [3, 4]. The subgrade is laid above the natural soil surface to sustain the loads coming from the traffic. A good subgrade soil is one that is strong, stable, and well-drained [5]. It should be able to support the loads from the pavement without deforming or becoming saturated. The subgrade soil should also be free of cracks, voids, and other defects [6]. The use of local materials can significantly reduce pavement construction costs. Soil stabilization procedures improve the quality of the local soil if it is not stable enough to handle wheel loads [7, 8]. Overall, application of soil stabilization procedures for pavement subgrade serves as a cost-effective and environmental friendly way to construct roads. Additionally, it also help to improve the drainage of the subgrade, and thereby prevent water damage to the pavement [5, 6, 9].

Silty sand soil, also commonly known as *Suddha* soil in the southern parts of Karnataka state, India, is a type of soil that is found in and around eight districts of the state [10]. It is characterized by its high proportion of sand and silt particles, and low clay content. It is extensively scattered below 1.5 meters of the ground surface and reaches depths of 15-20 meters. These

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soils are dispersive because they contain a high proportion of sodium ions which can exchange with other ions in the soil, such as calcium and magnesium. This process weakens the bonding between the soil particles, making them more susceptible to dispersion. These soils are found in India, the USA, Latin American countries, Greece, Thailand, and South Africa [11]. These soils are naturally vulnerable to erosion and segregation. They are liable to get eroded at moderate seepage rates, causing problems for embankments, roadways, canals, hydraulic structures, etc. The chemistry, mineralogy, and existence of salts in the soil affect its ability to resist erosion [12]. When soils are in a saturated condition, the attractive forces are less than the repulsive forces, causing particle segregation and a tendency for suspended particles to move. Figure 1 shows the silty sand formation and erosion of the embankment due to rain. Silty sand in a dry state possesses good strength; however, in a saturated condition, its shear strength reduces significantly. Numerous failures at foundations, road bases, and canal slopes grounded on silty sand have been documented [13–15]. Pavements constructed on these soils degrade more quickly due to the soil's poor strength. Replacement of soil with good soil is not a long-term solution because it is costly and has negative environmental consequences, and hence this soil shouldn't be rejected during the laying of pavements. Silty sand stabilization is a long-term solution that can be used to enhance the qualities of soil in-situ [16, 17].

Stabilization could be carried out in two ways, i.e., mechanically, and chemically. In mechanical stabilization, soil is combined with synthetic or natural fibers, while in chemical stabilization the soil is combined with chemicals like alum, pozzolana, etc. The cost of soil stabilization incorporating fibers is more economical than chemically treated soil, and the use of fibers is indeed environmentally friendly [18]. Adding areca fibers to soil can modify its engineering characteristics, including optimal moisture content (OMC), maximum dry unit weight (MDD), unconfined compressive strength (UCS), and California bearing ratio (CBR). Studies have shown that adding areca fibers to soil increases OMC and decreases MDD. Sudhakaran et al. [19] investigated the suitability of areca fiber as a soil reinforcement material in combination with bottom ash (BA) as a stabilizing agent. The addition of bottom ash and areca fiber significantly improved the UCS, CBR, and split tensile strength of the soil. Likewise, Das and Singh [20] showed that recron and areca nut coir fibers, both individually and in combination, can be effectively used to improve the strength of lateritic soil. Sujatha et al. [21] recognized that the rough and undulating surface of areca fiber is one of the vital characteristics that make it an efficient soil-reinforcing material. In turn, improved bridging action and soil reinforcing result from areca fiber's improved ability to interlock with soil particles. The study by Lekha et al. [22] found that the addition of 0.6% areca nut coir to lateritic soil resulted in an improvement in its properties. Their analysis revealed that the UCS and CBR values of the soil significantly increased with the addition of 0.6% areca nut coir and 3% cement. Both natural and synthetic fibers can be useful in enhancing the soil's bearing capacity. However, in some cases, natural fibers may be more effective than synthetic fibers. For example, a study by Kolathayar et al. [23] found that areca coir were more effective than polyvinyl alcohol fibers in improving the UCS values of soil–bottom ash mix. Alkali treatment of fibers can significantly improve the tensile and bond strength of a variety of natural fibers [24]. The use of arecanut fibers for soil stabilization is particularly promising in developing countries, where there is a need for sustainable and low-cost solutions to soil stabilization problems. Arecanut fiber-based soil stabilization technologies have the potential to make a significant contribution to sustainable infrastructure development.

Fig. 1 Silty sand formation and the view of erosion of the embankment

Table 1 Geotechnical properties of soil

Test		Test results	Reference IS code
Grain Size Analysis (%)	Gravel	3.5	IS: 2720-4 [25]
	Sand	58.6	
	Silt	34.9	
	Clay	3	
Atterberg Limits (%)	Liquid Limit	37.11	IS 2720-5 [26]
	Plastic Limit	NP	
Specific Gravity		2.57	IS 2720-3-1 [27]
Soil classification	ISCS	SM	IS: 1498 – 1970 [28]
Compaction characteristics (Standard compaction Test)	Optimum moisture content (%)	14.9	IS 2720-8 [29]
	Maximum dry unit weight (kN/m^3)	17.38	
Compaction characteristics (Modified compaction Test)	Optimum moisture content (%)	11.35	
	Maximum dry unit weight (kN/m^3)	18.44	

NP – Non-Plastic; *SM* – Silty Sand

India is the world's leading producer of arecanut, with around 50% of the total production coming from Karnataka and Kerala states. Although extensive research has been done on the use of various natural fibers, areca fibers have received less attention than other natural and synthetic fibers. There is a growing interest in using areca fibers in a variety of applications, including soil stabilization, composites, and geotextiles. While natural fibers have been explored for soil reinforcement, alkali-treated arecanut fibers, a readily available and sustainable resource, have received limited investigation in geotechnical applications. This study addresses this knowledge gap by evaluating their effectiveness in enhancing the strength of silty sand soil, a common yet challenging subgrade material for pavements. By incorporating IITPAVE analysis, we not only assess the fiber's impact on soil strength but also determine its suitability for real-world implementation in low-volume roads.

2 Materials and methodology

2.1 Silty sand soil

Silty sand soil was collected from Sarangipalya village of Tumkur district, Karnataka. Sieve analysis test results showed that silty sand consists of 3.5% of gravel, 58.6% of sand, 34.90% of silt, and 3% of clay. It had a specific gravity of 2.57 and a liquid limit of 37.11%. The silty sand is non-plastic soil and is classified in group 'SM' according to the Indian standard soil classification system (ISCS). Under standard Proctor compaction conditions, the silty sand had a maximum dry unit weight of 17.38 kN/m^3 and an optimum moisture content of 14.9%. Under modified Proctor compaction conditions, the silty sand had a maximum dry unit weight of18.44 kN/m^3 and an optimum moisture content of 11.35%. Table 1. presents the properties of silty sand soil tested as per Indian standard codes. In-situ dry unit weight of silty sand soil

Fig. 2 Grain Size Distribution curve of silty sand soil

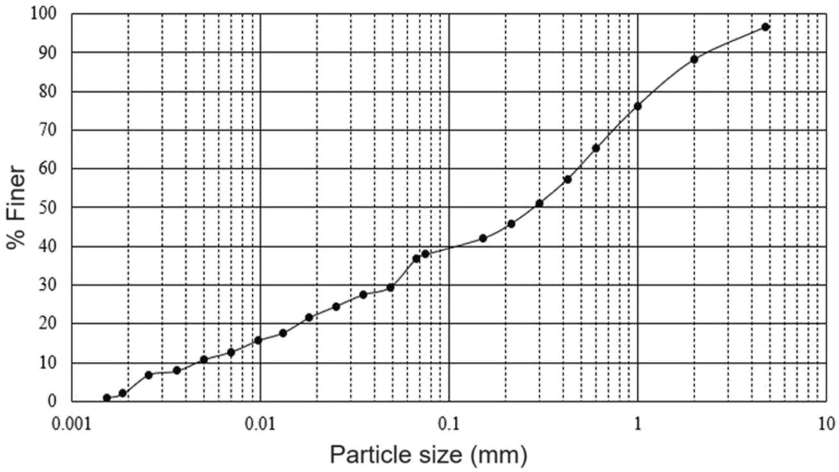

Table 2 Properties of areca fibers

Property	Value
Length (mm)	40
Diameter (mm)	0.2
L/D ratio	200
Density (g/cc)	1.12
Young's Modulus (GPa)	11.0 - 11.5
Tensile Strength (MPa)	250 - 275

was 15.89 kN/m^3 and the grain size distribution curve of the silty sand is shown in Fig. 2.

2.2 Areca fibers

Sourced from Bugudanahalli Village in Karnataka's Tumkur district, high-quality areca fibers were meticulously processed and collected. Areca fiber is a naturally available material obtained from the arecanut shell. Areca fiber consists of organic compounds such as cellulose, lignin, etc. Areca fiber shows greater tensile strength when the fibers are treated with chemicals. Areca fibers extracted from its cortex had variable lengths and diameters. The matrix contained both coarser and finer fibers. But for research, the coarser fibers were selected. Table 2 shows the physical and mechanical properties of the areca fibers used for the experiments.

2.2.1 Treatment of areca fibers

Areca fibers collected from the site were kept for drying until the moisture content in the areca fibers was completely reduced and became rather dry. The extracted fibers were soaked in a 6% NaOH solution for 24 hours, and after 24 hours, the fibers were washed with water and kept for drying for 1 day (24 hours). Figure 3(a) and (b) presents the areca fibers before and after the treatment, respectively.

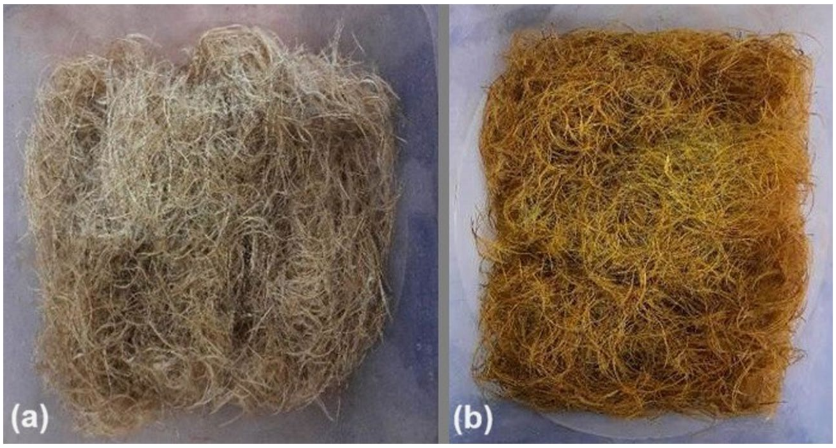

Fig. 3 Areca Fibers (**a**) before treatment (**b**) after treatment

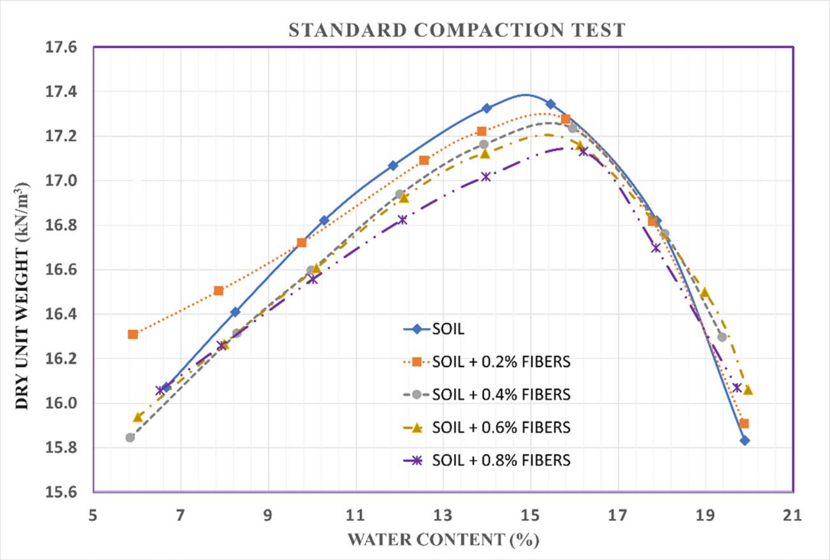

Fig. 4 Compaction curves of unreinforced and fiber-reinforced silty sand soil

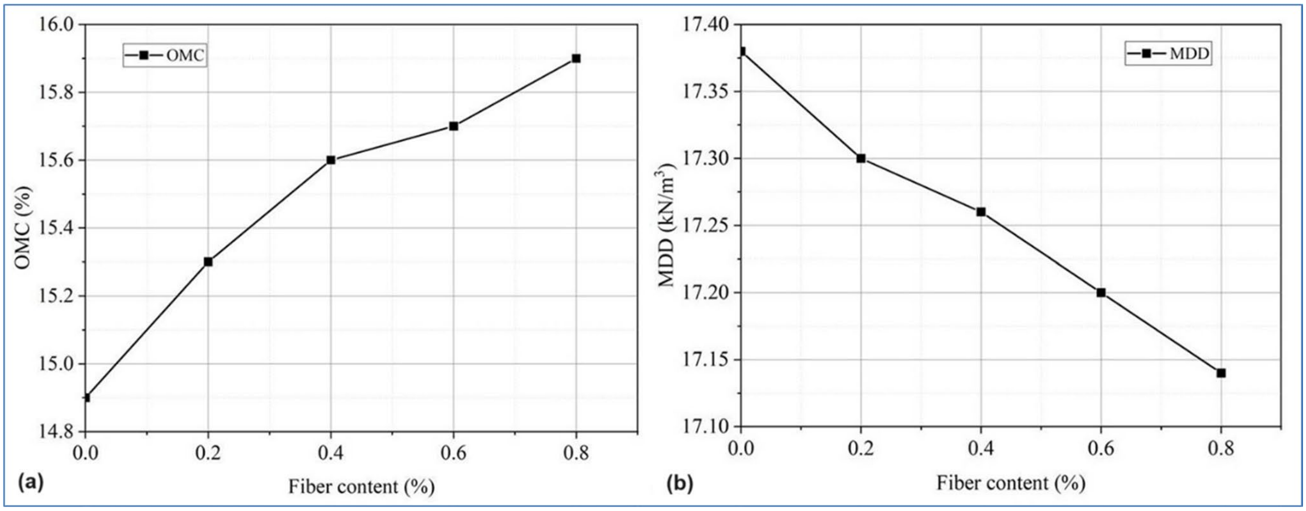

Fig. 5 (**a**) Variation of OMC (**b**) Variation of MDD for varying fiber content

2.3 Soil stabilization mix design

To ensure homogenous distribution and prevent fiber clumping, a meticulous dry mixing process was employed. The desired quantity of areca fibers was mixed with dry soil to produce the soil-fiber mixture. The fiber volume was determined in relation to the soil's dry weight. The fiber dosage ranged from 0% to 0.80% with an increment of 0.20%. Water addition followed a staged approach to further promote homogeneous mixing and prevent fiber agglomeration. Water was added a trio of times to a dry mixture of silty sand and fiber to achieve a homogeneous mixture. In the initial stage, the water was sprinkled on the soil to avoid the formation of clumps. In the second stage, nearly half the remaining water was added, and the mixture was hand-mixed thoroughly with a trowel for 10 minutes to promote good fiber dispersion throughout the soil matrix. The next step involved adding the remaining water, mixing it for roughly five minutes, and filling the specimen molds. The soil-fiber mixture is filled into the specimen molds with such care that it stays homogeneous throughout the entire operation. Samples curing time for CBR and UCS tests were 4 days and 24 hours, respectively. On the construction site, the earth is first graded, and then, prior to placement, the soil-fiber mixture is blended using a rotary paver. The detailed procedure for laying subgrade is discussed by Santoni and Webster [30].

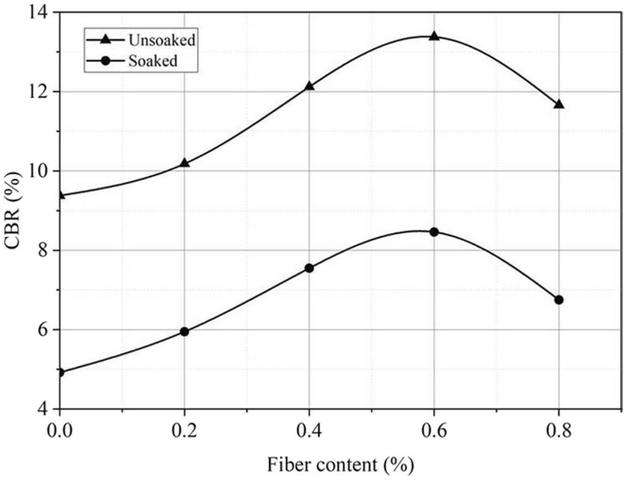

Fig. 6 CBR values of areca fiber reinforced silty sand soil in unsoaked and soaked conditions

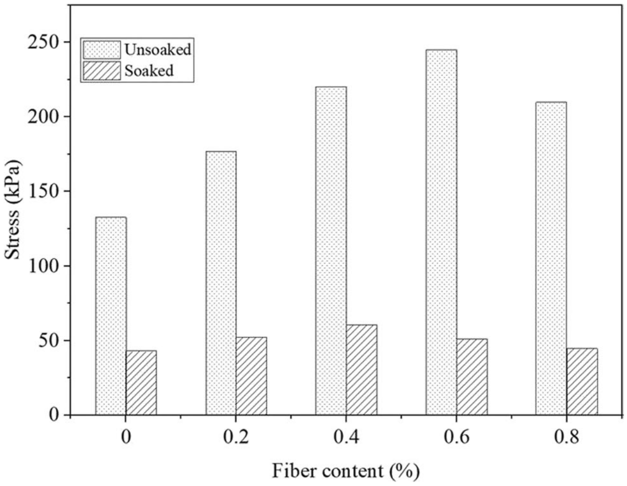

Fig. 7 UCS values of areca fiber reinforced silty sand soil in unsoaked and soaked conditions

Fig. 8 UCS sample (**a**) Unreinforced before loading (**b**) Unreinforced after loading (**c**) Soil+0.2% fibers before loading (**d**) Soil+0.2% fibers after loading

3 Results of experimental investigation and discussion

3.1 Effect of fiber reinforcement on soil compaction characteristics

Compaction tests were carried out on silty sand reinforced with varying percentage of areca fiber using the standard compaction method. The optimal moisture content (OMC) value increased from 14.9% to 15.9% as the fiber content increased from 0% to 0.8%. This is because the areca fibers absorb water, which increases the total water content of the soil-fiber mixture required to achieve maximum compaction. The maximum dry unit weight (MDD) value decreased from 17.38 kN/m^3 to 17.14 kN/m^3 as the fiber content increased from 0% to 0.8%. This is because the soil is replaced by lightweight fibers, which reduces the overall density of the compacted soil-fiber mixture. Figure 4 shows the compaction curves of unreinforced and fiber-reinforced silty sand soil. Figure 5(a) and (b) presents the variations in OMC and MDD for different dosages of areca fiber, respectively.

3.2 Effect of fiber reinforcement on California bearing ratio

California bearing ratio (CBR) tests were carried out on silty sand soil reinforced with various percentages of areca fiber, assessing its impact in both unsoaked and soaked conditions. The results demonstrated a positive correlation between fiber content and CBR value, signifying increased soil strength. The areca fibers, when incorporated into the silty sand soil matrix, bind or link cracks and voids. This helps transfer stress more efficiently between soil particles, leading to increased strength and reduced crack propagation. In the unsoaked condition, the CBR value rose significantly, from 9.38% to 13.38%. Soaked samples also exhibited improvement, with a rise from 4.92% to 8.46%. This enhancement can be attributed to the fibers' role in bridging soil particles and hindering their movement under stresses, effectively increasing the soil's shear resistance. Notably, the maximum CBR value was achieved at an optimal fiber content of 0.6%. The effect of fiber content on CBR value is more pronounced in the unsoaked condition, which suggests that areca fibers can be used to improve the stability of silty sand subgrades in pavements, particularly in areas with minimal rainfall. Figure 6 shows the variation in CBR values under both unsoaked and soaked conditions. The load versus penetration plots (Fig. 12), depict the crucial relationship between the applied load and the resulting penetration depth, offering valuable information about the soil's deformation behavior under stress.

Fig. 9 UCS samples kept for soaking for 24 hours

3.3 Effect of fiber reinforcement on unconfined compression strength (UCS)

Unconfined compressive strength (UCS) tests were carried out on silty sand soil reinforced with various percentages of areca fiber in both unsoaked and soaked conditions. The results showed that the UCS value of the soil-fiber mixture increased with increasing fiber content, up to a maximum value at 0.6% fiber content. Further addition of fiber up to 0.8% decreased the UCS value. This is likely due to the silt particles in the soil, which can alter the physical properties of the soil after coming into contact with water. The effect of areca fiber on the UCS value of silty sand soil is more pronounced in the unsoaked condition than in the soaked condition. This is because water can weaken the bond between the areca fiber and the soil particles. Additionally, the silt

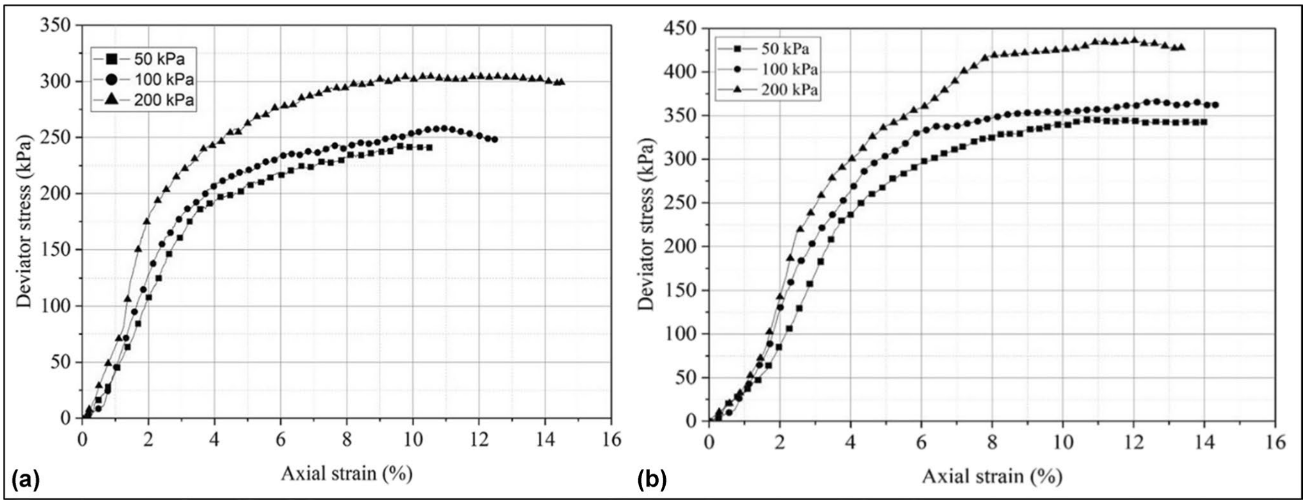

Fig. 10 Deviator stress v/s Axial strain curves obtained from the triaxial test (**a**) for the unreinforced soil (**b**) for the soil mixed with 0.6% fibers

particles in the soil can swell when they come into contact with water, which can also reduce the UCS value of the soil-fiber mixture. Figure 7 shows the UCS values for different areca fiber content under both unsoaked and soaked conditions. Figure 8(a) and (b) show the unreinforced UCS sample before and after loading, respectively. Unreinforced soil sample failed along well-defined shear plane. Figure 8(c) and (d) show the soil + 0.2% fibers sample before and after loading, respectively. Fibers aid in distributing the stress more uniformly, leading to a more diffuse failure pattern. Figure 9 presents the UCS samples soaked in water for 24 hours. The saturation by capillary rise method was implemented wherein the UCS samples are covered by the membrane, and the water must be filled up to two-thirds of the sample's height. Figure 13 presents the stress-strain curve from UCS test performed on unsoaked soil samples. An unreinforced soil sample exhibited a brittle post-peak behavior. The stress dropped rapidly after reaching the peak, indicating a sudden failure. In contrast, fiber-reinforced soil samples showed a more ductile response. The presence of fibers helps bridge cracks and prevents complete disintegration after peak stress. Areca fibers help maintain some residual strength after peak stress, leading to a more controlled deformation compared to the sudden failure of unreinforced soil. Unreinforced silty sand (unsoaked sample) exhibited a failure axial strain of only 0.02228, whereas the sample reinforced with 0.6% fibers achieved a much higher strain of 0.0513. This represents an increase of over 130%. This enhanced strain capacity indicates that the fiber-reinforced soil can undergo significantly larger deformations before failure compared to the unreinforced sample.

Table 3 Deviator stress and axial strain of various areca fiber reinforced soil samples

Cell pressure	Soil sample	Deviator Stress (kPa)	Axial strain (%)
50kPa	Silty sand	242.59	9.53
	Silty sand+0.2% fibers	275.69	10.32
	Silty sand+0.4% fibers	309.14	10.48
	Silty sand+0.6% fibers	345.56	10.65
	Silty sand+0.8% fibers	316.49	9.82
100kPa	Silty sand	258.73	10.78
	Silty sand+0.2% fibers	292.21	11.41
	Silty sand+0.4% fibers	327.22	11.62
	Silty sand+0.6% fibers	367.38	12.54
	Silty sand+0.8% fibers	331.50	11.21
200kPa	Silty sand	305.09	10.41
	Silty sand+0.2% fibers	359.56	10.37
	Silty sand+0.4% fibers	391.37	11.53
	Silty sand+0.6% fibers	435.95	12.03
	Silty sand+0.8% fibers	379.44	11.24

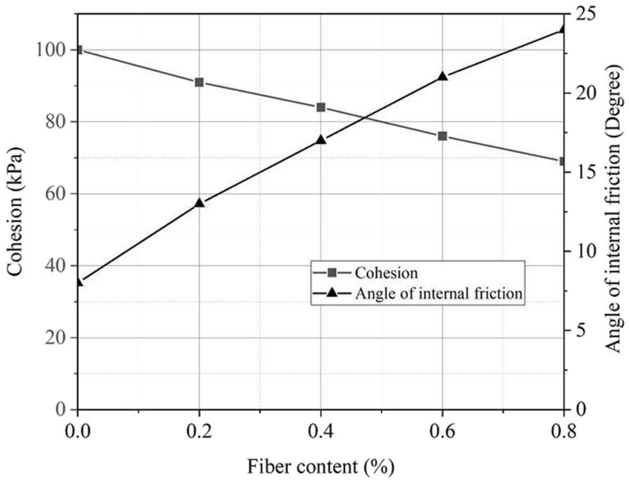

Fig. 11 Variations in cohesion and angle of friction for different fiber dosage

3.4 Effect of fiber reinforcement on Triaxial shear strength

Triaxial tests were conducted on silty sand reinforced with varying percentages of areca fiber at different confining

Table 4 Pavement layer thickness as per Indian Standard and the analysis points

Traffic conditions	Pavement layers	Thickness(mm)	Analysis points (mm)
T_7	Granular Sub Base (GSB)	150	75 and 375
	Base Course	150	
	Surface Course	75	
T_8	GSB	200	75 and 425
	Base course	150	
	Surface course	75	
T_9	GSB	150	50 and 425
	Base course	225	
	Surface course	50	

Table 5 Horizontal tensile strain for different traffic conditions

Traffic conditions	Allowable Strain	Actual Strain from IITPAVE	Remarks
Areca fiber reinforced silty sand soil subgrade			
T_7	1.1186×10^{-3}	0.9320×10^{-3}	Safe
T_8	1.0220×10^{-3}	0.7572×10^{-3}	Safe
T_9	0.9600×10^{-3}	0.8053×10^{-3}	Safe
Unreinforced silty sand subgrade			
T_7	0.60707×10^{-3}	0.4841×10^{-3}	Safe
T_8	0.5460×10^{-3}	0.4556×10^{-3}	Safe
T_9	0.5079×10^{-3}	0.5439×10^{-3}	Not safe

pressures (50 kPa, 100 kPa, and 200 kPa). Soil mixed with 0.6% fibers at a confining pressure of 50 kPa exhibited the maximum deviator stress value of 345.56 kPa. The corresponding values at confining pressures of 100 kPa and 200 kPa were 367.38 kPa and 435.95 kPa, respectively. Figure 10(a) and (b) show the variations in deviator stress and axial strain for unreinforced soil and soil with 0.6% fibers, respectively. The remaining soil samples showed the same trend, and the values are presented in Table 3. The shear strength properties, such as cohesion (C) and angle of internal friction (ϕ), were obtained from the above tests. The C-value decreased, and the ϕ-value increased, as the percentage of fibers increased. The cohesion value varied from 100 to 69 kPa, and the angle of friction ranged from 8 to 24 degrees. Figure 11 shows the cohesion and angle of friction values for different fiber dosages. Randomly distributed areca fibers can interlock with silty sand soil particles, hindering their movement. Oriented fibers, if present, act as miniature reinforcing elements, taking up tensile stresses and preventing soil matrix failure.

Table 6 Vertical compressive strain for different traffic conditions

Traffic conditions	Allowable Strain	Actual Strain from IITPAVE	Remarks
Areca fiber reinforced silty sand soil subgrade			
T_7	1.770×10^{-3}	0.4225×10^{-3}	Safe
T_8	1.0611×10^{-3}	0.3965×10^{-3}	Safe
T_9	0.9855×10^{-3}	0.3508×10^{-3}	Safe
Unreinforced silty sand subgrade			
T_7	1.118×10^{-3}	0.9465×10^{-3}	Safe
T_8	1.0229×10^{-3}	0.8961×10^{-3}	Safe
T_9	0.9600×10^{-3}	0.9961×10^{-3}	Not safe

4 Pavement analysis with IITPAVE software

IITPAVE is a software program developed under the MoRTH Research Scheme by the Indian Institute of Technology Kharagpur as an improved version of FPAVE. The IITPAVE program evaluates how flexible pavement performs under various loads using the finite element method (FEM). The software aids in the analysis of a linear elastic layered pavement system by accounting for a number of variables such as traffic volume, weather, material properties and quality (IRC:37-2018 [31]). The flexible pavement (considering unreinforced and 0.6% areca fiber reinforced silty sand soil as subgrade) was simulated in accordance with IRC:37-2018 [31] standards before IITPAVE analysis was performed. The thickness of each layer of the pavement structure was identified from IRC:SP-72-2015 [32]. For this study, three traffic conditions were chosen: 1 million standard axles (msa) (T_7), 1.5 msa (T_8), and 2 msa (T_9). For analysis, we focused on the CBR values obtained under soaked conditions: 8.46% for the subgrade reinforced with 0.6% areca fiber and 4.92% for the unreinforced soil. The required inputs for IITPAVE analysis are the number of layers, resilient modulus/elastic modulus, Poisson's ratio, and thickness of each layer. The analysis was carried out considering the wheel load assembly for a single-axle twin-wheel load. A load of 20000 N was taken for a single wheel. Poisson's ratio taken was 0.35 for all the layers, and the tyre pressure taken was 0.56 MPa. Four analysis points beneath the wheel load assembly were considered, with the dual wheel's centre line as the starting point for calculations of the analysis point depth and radial distance, which are computed vertically from the top pavement layer. For low-volume roads, 80% reliability was established. The actual strains obtained from the IITPAVE software were compared with the allowable strains obtained from IRC standards. The provided pavement thickness was considered safe and satisfactory if the allowable strains were greater than the actual strains. Table 4 presents the various pavement layer thicknesses and different analysis points that were studied. Tables 5 and 6 show the horizontal tensile strains and vertical compressive strains under different traffic conditions, respectively.

Allowable strains calculated using IRC: 37- 2018 [31] showed greater values than actual strains obtained from IITPAVE software for T_7 and T_8 traffic conditions. As a result, the assumed thickness of the pavement was appropriate, and the design of the pavement is considered safe. With reference to T_9 traffic, the results suggest that pavements with areca fiber-reinforced subgrades are safe, while unreinforced silty sand subgrades are not recommended.

5 Conclusions

A series of experiments was conducted on the silty sand soil-fiber mixture to determine the strength of the soil after stabilization. Based on the results of stabilization experiments on silty sand mixed with areca fibers, the following conclusions are drawn:

1. The inclusion of areca fibers in silty sand improved the engineering properties of the soil.
2. The addition of fibers increased the optimum moisture content (OMC) and decreased the maximum dry unit weight (MDD) values. Silty sand without fibers had an OMC of 14.9% and a MDD of 17.38 kN/m^3. However, the soil mixed with the optimum fiber dosage of 0.6% had an OMC of 15.7% and a MDD of 17.2 kN/m^3.
3. CBR test results showed that increasing the fiber content increased the CBR value. According to IRC: SP:72-2015 [32], a CBR value of 7-9% is considered good for a subgrade. Therefore, the results showed that fibers can be used as reinforcement in subgrade soils. The CBR value is optimum at 0.6% fiber concentration.
4. UCS results showed that the shear strength increased, and the strain value decreased upon the addition of areca fibers. The optimum UCS value in the unsoaked condition was obtained at 0.6% fiber content, and in the soaked condition, it was obtained at 0.4% fiber content.
5. Triaxial results showed that the deviator stress increased up to 0.6% fibers in the soil-fiber mixture and then decreased upon further addition of fibers with an increase in cell pressure.
6. According to IITPAVE analysis, the provided thickness of the layers was appropriate, and the thickness of pavement layers of the modified subgrade was reduced compared to that of the conventional subgrade. This reduces the cost of road construction. Additionally, since the areca fibers are naturally available, the stabilization process becomes cost-effective and contributes to the construction of subgrade at a reduced cost.

Appendix

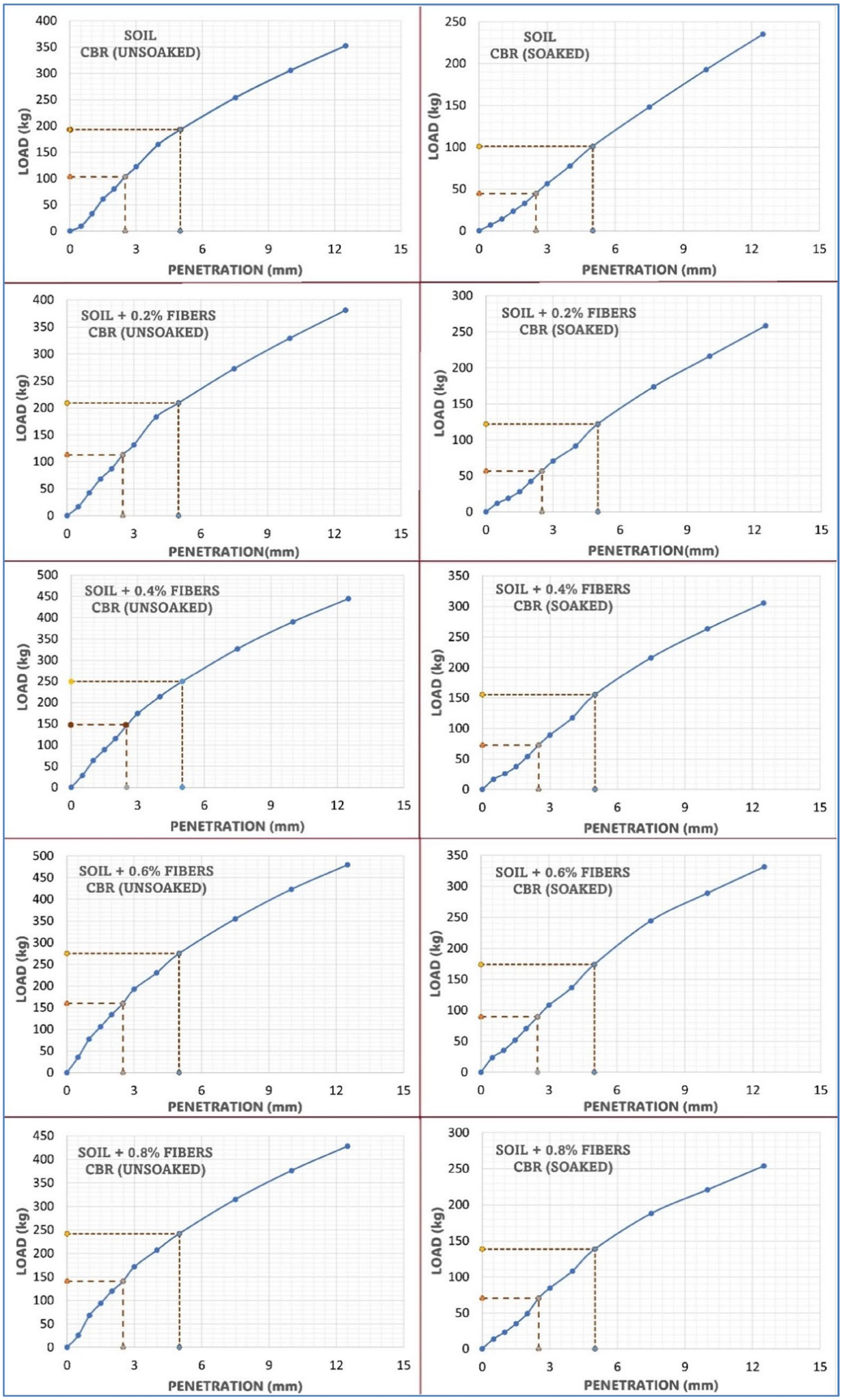

Fig. 12 Plot of Load versus Settlement curve of CBR test

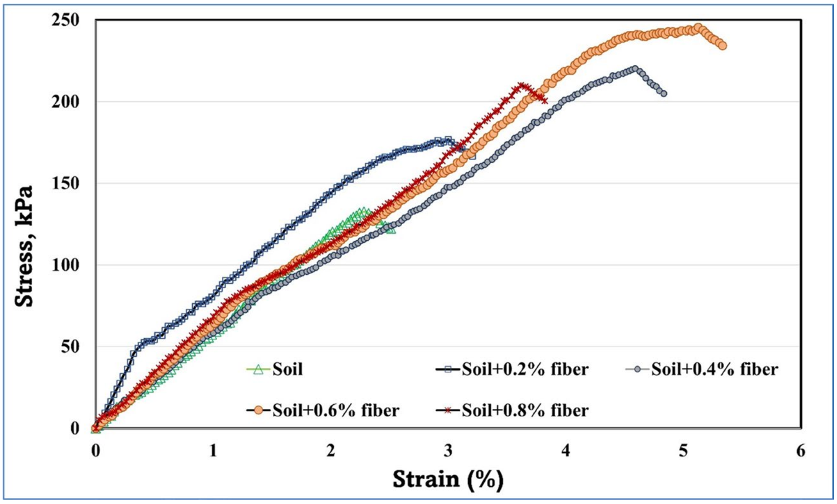

Fig. 13 Stress versus strain curve from UCS test performed on unsoaked soil samples

Authors' contributions MSB: Conceptualization; Methodology; Editing & Reviewing, Supervision. SSS: Writing – original draft, Experimental Study. DP, SRN: Visualization, Writing – Editing & Reviewing, Validation.

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Data availability The datasets generated during and/or analyzed during the current study are available from the authors on reasonable request.

Declarations

Institutional review Not applicable.

Informed consent Not applicable.

Conflicts of interest The authors confirm that there is no known conflict of interest associated with this publication and there have been no financial gains from this work that could have influenced its outcome.

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