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Original Article

Stabilization of Peat Soil with Silica Fume and Areca Fiber as Reinforcement: An Experimental Investigation

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Abstract *- The fast expansion of municipal areas and the rising demand for construction have led to a lack of land with optimal soil conditions. Consequently, builders often must utilize locally available weak soil, making soil stabilization an essential process. These techniques enhance soil strength and durability by altering its properties. While various soil stabilization techniques have been explored, limited studies focus on the combined outcome of silica fume and areca fiber in improving the strength and durability of peat soil in the context of Ziro Valley, Arunachal Pradesh. Various tests were done on soil specimens, including physical and index properties, compaction, UCS, CBR, SEM and EDX. Areca coir (20-30 mm) improved soil properties up to 0.5% of its dosage with soil, but it encounters distribution issues at higher doses. Varied weight ratios of silica fume 6%,8% and 10% and 0.3%,0.5% and 0.7% areca fiber are used according to the soil type to achieve the best possible conditions. The strength of peat is significantly enhanced with the incorporation of silica fume due to its cementitious compound, leading to a rise in MDD and a decrease in OMC. The inclusion of areca reinforced in soil decreases MDD and increases OMC. In this study, the S+8%SF+0.5%AF mixture demonstrated the highest UCS value of 369.256 kPa after 28 days of curing, indicating its effectiveness in enhancing the strength of peat soil. Additionally, the S+10%SF+0.5%AF mixture showed the most significant improvement in CBR values, increasing from 3.45% to 13.71% (unsoaked) and from 2.27% to 11.1% (soaked). This represents a 388.98% increase compared to untreated peat soil. The S+10%SF+0.5%AF mixture thus meets the design requirements recommended for subgrade soil treatment. Microstructural analysis via EDX and SEM enhances understanding of soil strength and stability factors. Silica fume enhances soil stability, while areac fiber strengthens it, as shown through compaction, UCS, and CBR tests. Using these waste materials offers an economical and sustainable solution in engineering.*

Keywords *- Silica fume, Areca fiber, Soil stabilization, Sustainable.*

1. Introduction

Utilizing local materials, such as indigenous soils, can significantly reduce construction expenses. However, if the stability of the native soil doesn't fulfil the desired soil properties, soil stabilization techniques can be employed to enhance its properties. These methods enhance the soil's stability and load-bearing capacity, ensuring a robust foundation for construction projects while taking advantage of cost-effective local resources. The choice of soil stabilization can be influenced by soil type and its nature, performance, and environmental factors to obtain the desired characteristics of soil. Silica fume, often referred to as micro silica, is Silicon Dioxide (SiO_2) in an amorphous, non-crystalline polymorph that is present as a round-shaped particle [16]. Silica fume is collected from flue gases generated through the manufacture of silicon and ferrosilicon alloys in electric arc furnaces. Silica fume is an outcome of silicon, which has a large surface area and microparticles measuring about 200 nm-1100 nm [1]. Silica fume has a specific gravity of about 2.22 [8]. The production of Portland cement results in significant annual Carbon Dioxide (CO_2) emissions. Therefore, utilizing silica fume becomes crucial as it can reduce the amount of cement required in various applications. Additionally, silica fume's fine particles can create pozzolanic compounds and act as a filler in compacted soil, enhancing its structural integrity and optimizing pore spaces, thus strengthening its structures and optimizing its pore spaces [17]. In concrete mixtures, silica fume is often used as a supplementary cementitious material, as it improves the material's properties, enhancing its strength, durability, and resistance to chemicals and wear. Combining Silica fume, Nano silica, and fibers in pavements improves performance and durability, creating sustainable pavements which benefit both the mining industry and society. The pozzolanic effects and pore-filling of silica fume contribute to enhanced soil and more visible compressive strength compared to fly ash [6], which has unfriendly effects towards the environment. The usage of this alternative might result in cleaner creation. Areca fiber is low-cost, widely available, and a perennial crop with high potential. It is introduced in the current study as a promising natural fiber.

Most of Asia, East Africa and the tropical Pacific are home to the areca palm species. Southeast Asia has extensive areca farming, including several Pacific Ocean islands, like Indonesia, New Guinea, and the West Indies. The area is abundant in India, including states like

Karnataka, Kerala, and Assam. They are obtained from the husk, or outer layer, of areca palm seed. These fibers can be broadly divided into two categories. White areca fibers are commonly used to make traditional products like crafts, baskets, etc. They are also used in eco-friendly packaging. Brown areca fibers often make ropes, mats, brushes, and other utility items. They are also known for their strength and are utilized in various traditional and industrial applications. There is virtually little areca used as soil-reinforcing fiber. The areca fiber acts as a reinforcement to the soil, which contributes to improved engineering properties, including tensile strength, shear strength, CBR, and load-carrying properties [15]. This enhancement is evident under various stress conditions [4]. Natural fiber stabilization is more cost-effective due to its abundance. When fiber reinforcement is used in soil, its tensile strength is improved significantly. The fibre's quantity and length directly affect the CBR Value [18]. Pretreatment of areca fiber is done with several chemicals for soil stabilization to increase its durability, such as Potassium Hydroxide (KOH), Acetic Acid (CH_3COOH) solution [14], or linseed oil [6] as fiber is biodegradable.

2. Material and Methodlogy

The primary goal of the test was to explore the effectiveness of utilizing silica fume in conjunction with areca fiber as soil reinforcement for stabilizing peat soil. The silica fume was uniformly distributed within the soil, and various proportions of 6%, 8%, and 10% based on the soil weight were used. Additionally, areca fiber was incorporated at different percentages of 0.3%, 0.5%, and 0.7% of the soil weight.

2.1. Soil

The soil samples were taken from Siro Village, in the Lower Subansiri area of Arunachal Pradesh, India's Ziro Valley. The sampling site's precise geographical coordinates were documented as 27.51 N latitude and 93.84 E longitude. Soil samples were obtained below 1 meter to ensure the representation of the soil's characteristics in that specific region. The selected location and sampling depth offer valuable insights into the soil characteristics and behaviour of the soil in the studied area. The soil underwent pulverization and oven-drying procedures prior to testing. Twigs and large lumps were removed to ensure a clean sample. Regular water was utilized throughout the study, except in cases where standard specifications specifically mandated distilled water.

Various tests were done to assess the physical properties or index properties of the natural organic soil sample. The physical properties assessment encompassed various tests, including pH measurements, specific gravity, water content, particle size distribution, Atterberg Limits, and Loss on Ignition.

The water content of the collected soil sample was subjected to drying in an oven at 105°C for 24 hours, following the procedures specified in IS 2720 (Part-2)-1983. The specific gravity of the peat soil sample was evaluated using the pycnometer method, following the guidelines outlined in IS 2720 (Part-3)-1983. The liquid limit was determined using the Casagrande apparatus, adhering to the recommended procedures according to IS 2720 (Part-5)-1983.

Table 1. General properties of the parent soil

Property	Result
Water Content	51.35%
Specific Gravity	1.63
Sieve analysis	
1 Gravel (> 4.75mm)	NIL
2 Sand (0.075mm - 4.75mm)	25.10%
3 Silt and clay (0.075mm -0.002mm)	74.90%
Bulk unit wt. of peat soil	1.59 g/cc
Liquid limit	52.08%
Plastic limit	35.17%
Plasticity Index	Highly plastic
OMC	30%
pH	4.96
Organic Content	28.7
IS soil classification	OH (peat)

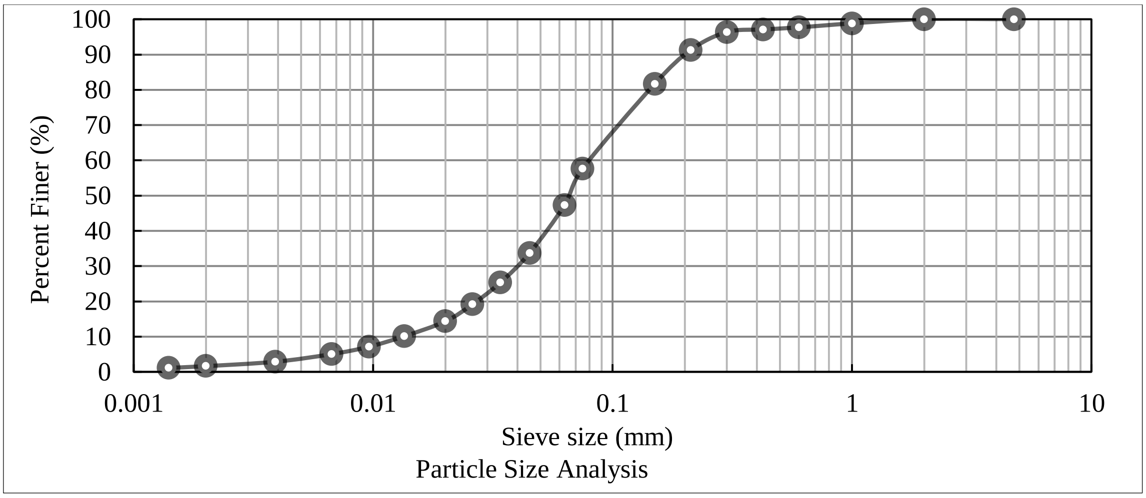

Fig. 1 Particle size distribution curve of peat soil

The peat soil's index properties were examined and documented in Table 1 following the guidelines of IS-2720 (part-IV)-1985. Figure 1 depicts the gain size analysis of soil. These properties furnish crucial insights into the characteristics and behaviour of the peat soil. Siiro Village, in the Ziro Valley of Arunachal Pradesh, India, is where peat soil was collected. The precise geographical coordinates for the sampling site were recorded as 27.51°N latitude and 93.84°E longitude, ensuring accurate identification of the specific location. A depth of approximately 1 meter was dug to collect soil samples and to ensure representative characteristics of the peat soil in that particular region. Before proceeding to test and analysis, peat soil was subjected to oven drying to remove any excess moisture and achieve a consistent moisture content for testing.

2.2. Silica Fume

Silica fume is an ultrafine powder as a byproduct of silica and ferrosilicon alloy in electric arc furnaces, which involves high-temperature reduction of quartz with raw material such as coke. Silica fume is generated during the manufacturing process of ferrosilicon and silicon, consisting of ultrafine airborne particles 100 to 150 times smaller than cement particles [17]. Proper disposal of silica fume is a significant concern for environmentalists, as leaving it untreated in the environment can pose serious health risks [19]. It's also obtained in silicon alloys like ferromanganese and ferrochromium manufacturing. Comprising over 90% extremely fine amorphous Silicon Dioxide (SiO_2), SF is known as micro silica or condensed silica. The specific gravity of the greyish Silica fume taken for the test is 2.

Table 2. Silica fume chemical composition

Standard	Composition
SiO_2	93.54%
Al_2O_3	0.43%
Fe_2O_3	0.94%
CaO	0.49%
MgO	1.71%
Na_2O	0.82%
K_2O	1.04%

Source: Banar et al. 2022

Fig. 2 Silica fume

2.3. Areca Fiber

Areca fiber is low-cost, widely existing, and a persistent crop with high potential; it is introduced in the current study as a promising natural fiber that can be used as soil reinforcement. Areca in India is abundant in states like Karnataka, Kerala, and Assam. They are obtained from the areca palm seed's husk or outer layer. These fibers can be broadly divided into two categories. White areca fibers are commonly used to make traditional products like crafts, baskets, etc. They are also used in eco-friendly packaging. Brown areca fibers often make ropes, mats, brushes, and other utility items. They are also known for their strength and are utilized in various traditional and industrial applications. There is virtually little areca used as soil-reinforcing fiber. Natural fiber stabilization is more cost-effective due to its abundance. It is inexpensive and widely available, and a perennial crop with high potential is introduced in the current study as a promising natural fiber. The practice of areca farming is areca nut, which is often used commercially, and chewy gutka. Areca fibers are made from the areca palm seed's husk or outer layer**.** When fiber reinforcement is used in soil, its tensile strength is improved significantly. The specific Gravity (G) obtained after the density bottle test was obtained to be 1.

Table 3. Physical properties of areca fiber. (Source Chauhan et. al. 2008)

Dia	Length of Fiber				Density (g/cm3)
	Short	medium	Long	Average	
0.285-0.89	18-29	30-38	39-46	29-38	1.05-1.25

Fig. 3 Areca fiber length

Fig. 4 Areca coir fiber

Fig. 5 Areca coir immersed in water with linseed oil

Figure 5 depicts the areca fiber taken for the test, measuring 20-30 mm long. Areca fiber is treated beforehand for soil stabilization to increase its durability as it is biodegradable. Figure 6 shows the coir fiber taken out from the arecanut for this test. Figure 7 shows the treatment process for effective utilization. Areca fiber was first immersed in water for 15 days, and then linseed oil was mixed at 0.6% of fiber weight. This was later kept for drying for 30 min at room temperature and then oven-dried for 2 hrs. This treatment enhanced the morphology of fiber surface, giving a rough surface and thus increasing fiber durability.

2.4. Methodology

The primary aim of the investigation was to thoroughly assess the potential utility of silica fume, when combined with cement, as a stabilizing agent for peat soil. By systematically incorporating varying proportions of silica fume (6%, 8%, and 10% by weight of the soil) into the soil samples, the study aimed to discern the optimal dosage for achieving effective stabilization.

Additionally, after the treatment process, the introduction of areca fiber into the mix was pursued to bolster the soil's durability and enhance its overall morphology. This involved exploring different percentages of areca fiber (0.3%, 0.5%, and 0.7% by weight of the soil. The collective utilization of silica fume and areca fiber was intended to synergistically improve the properties of peat soil and bolster its stability.

By delving into these diverse combinations, the study sought to pinpoint the ideal ratio of silica fume to areca fiber for achieving optimal soil stabilization outcomes. Through meticulous experimentation and comprehensive analysis, the investigation aimed to offer a useful purpose on the practicality and efficacy of employing silica fume as an additive alongside areca fiber for stabilizing peat soil.

3. Experimental Programs

The study investigated the effects of different mix compositions on soil properties, incorporating Silica Fume (SF) and Areca Fiber (AF) with varying curing times. The mix designations included pure Soil (S), Soil-Silica Fume Mixes (S+SF) with silica fume percentages of 6%, 8%, and 10%, and Soil-Areca Fiber Mixes (S+AF) with fiber content of 0.3%, 0.5%, and 0.7%. Additionally, combined mixes (S+SF+AF) incorporated both silica fume and areca fiber in the same proportions. These samples were examined after curing durations of 0, 7, 14, and 28 days to analyze their strength and compaction behavior.

3.1. Compaction Test (IS: 2720-Part 7, 1992)

Compaction is a key process for increasing soil density using mechanical energy, significantly influencing properties like compressibility, permeability, and shear strength. In this experiment, light compaction tests were done to assess the OMC and MDD of the soil samples, offering valuable insights into their compaction characteristics. The mix designations, detailed in Table 3, include combinations of Soil (S), Silica Fume (SF), and Areca Fiber (AF). Pure Soil (S) served as the control, while other mixes involved varying proportions of silica fume (6%, 8%, 10%) and areca fiber (0.3%, 0.5%, 0.7%), alone or in combination. For example, S+6SF+0.3AF represents 6% silica fume, 0.3% areca fiber, and the remaining soil. These designations facilitated systematic analysis of compaction and strength characteristics.

The standard Proctor compaction test performed on the parent peat soil yielded an OMC of 30% percent and an MDD of 13.25 kN/m3. Subsequent sections of this study will delve into the variations observed in MDD and OMC when different proportions of silica fume and areca fiber are introduced. These sections will explore the influence of silica fume and areca fiber on the compaction characteristics of the peat soil and analyses how they affect the values of MDD and OMC.

3.2. Unconfined Compression Test (IS 2720-Part 10, 1991)

The investigation examined the strength properties of various mix proportions incorporating silica fume and areca fiber. Specimens were prepared at their MDD and OMC values for Unconfined Compressive Strength (UCS) tests and cured for 0, 7, 14, and 28 days. Outcomes displayed adding silica fume and areca fiber significantly enhanced UCS values, with curing further improving strength, particularly after 28 days. The UCS test results for soil-silica fume mixes (e.g., S+6%SF, S+8%SF, S+10%SF), soil-areca fiber mixes (e.g., S+0.3%AF, S+0.5%AF, S+0.7%AF), and combined soil-silica fume-areca fiber mixes (e.g., S+6%SF+0.3%AF, S+8%SF+0.5%AF). The combined effect of silica fume and areca fiber yielded substantial improvements in strength, validating their potential in stabilizing peat soils.

3.3. California Bearing Ratio Test (IS: 2720-Part 16, 1992)

The current study aims to evaluate the effectiveness of Silica fume and Areca fiber in stabilizing the peat soil of Ziro town. By assessing the improvement in the strength characteristics of parent peat soil treated with several ratios of silica fume and Areca fiber using the CBR test, this investigation will determine whether these stabilizers are suitable for enhancing peat soil's complete firmness and bearing capacity. The findings will contribute to understanding the potential of silica fume and Areca fiber as viable options for stabilizing peat soil, aiding engineers and professionals in informed decision-making for geotechnical projects involving peat soil.

Following a curing period of 14 days with different percentages of soil-silica fume mixes, Areca fiber mixes, and soil-silica fume-Areca fiber mixes, California Bearing Ratio (CBR) tests were conducted on peat soil samples in accordance with IS 2720 (Part 16)-1987 (reaffirmed 2022). A set of unsoaked and soaked CBR was performed on different mixtures to assess how silica fume and areca fiber influence the CBR properties of peat soil. Preparation of the

CBR test involved compacting the soil with various combination silica fume and areca fiber mixes, determining the OMC and MDD values for each mixed specimen and conducting CBR tests on the molds submerged in water for 96 hours after draining excess water of

3.4. Microstructure Analysis

Microstructure analysis is vital for understanding peat soil's internal composition and characteristics. In this study, Scanning Electron Microscope (SEM) micrographs were utilized to investigate the microstructural features of untreated peat from Arunachal Pradesh. X-ray analysis is frequently utilized to assess the mineralogical composition of different materials, including soil samples.

4. Result and Discussion

4.1. Compaction Behaviour of Soil-Silica Fume Mix

Table 4. MDD and OMC of soil-areca fiber mixes

Mix	MDD (kN/m3)	OMC (%)
S	13.25	30
S+0.3%AF	13.23	30.1
S+0.5%AF	13.21	32.3
S+0.7%AF	13.18	32.4

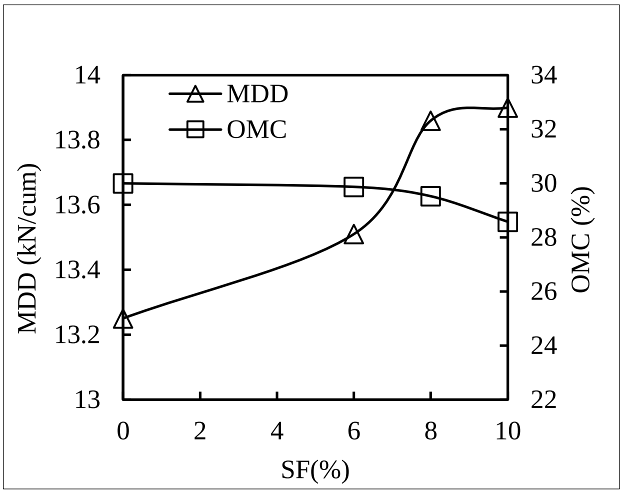

fig. 6 Variation of MDD and OMC of peat-silica fume mixes

The MDD value increases from 13.2 kN/m3 to 13.9 kN/m3. While OMC decreases from 30% to 28.5%, as depicted in Figure 8. The total particle surface of the mixture increased when silica fume was added, varying with its content compared to the raw sample [1]. Consequently, the composite samples exhibited a decrease in the optimum water content [14]. This may be due to higher specifics and pozzolanic reaction formed when soil mixes with silica fume and water that binds the soil grains. The difference in specific gravities between peat soil (G=1.63) and silica fume (G=2.2) may explain the increase in MDD of the soil-silica fume mix samples.

4.2. Compaction Behaviour of Soil-Areca Fiber Mix

Figure 7 depicts the difference in MDD and OMC of areca fiber when mixed with soil. Areca fiber dosage was taken as 0.3%, 0.5% and 0.7% of dry mass of soil. Table 4 shows that the proportion of fiber dosage increases, and results show decreases in MDD and an increase in OMC. The MDD values decrease from 13.25 kN/m3 to 13.18 kN/m3. At the same time, OMC value increases from 30% to 32.4%.

The rise in the MDD of soil is due to the incorporation of lightweight reinforcing materials replacing soil, the density of soil being 1.59 g/cc and that of areca fiber being 1.2 g/cc. With the incorporation of coir simultaneously, the OMC of the soil improves proportionally as the proportion of fiber increases. Conversely, areca fibers exhibit notable water absorption characteristics, contributing to improving the OMC [10].

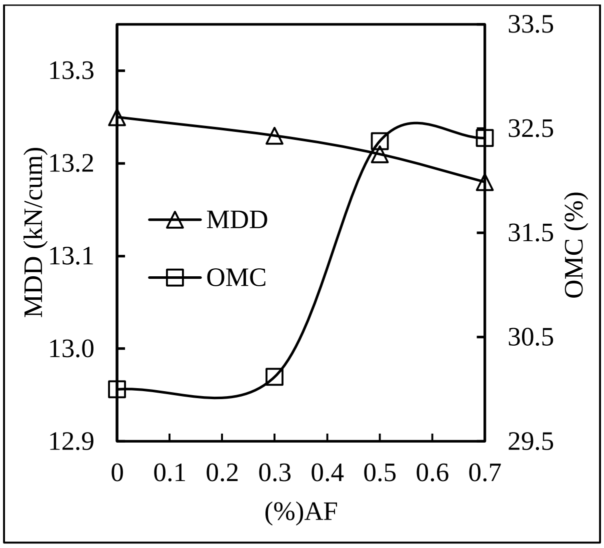

Fig. 7 Variation of MDD and OMC of peat-areca fiber mixes

4.3. For the Peat-Silica-Areca Fiber Mix

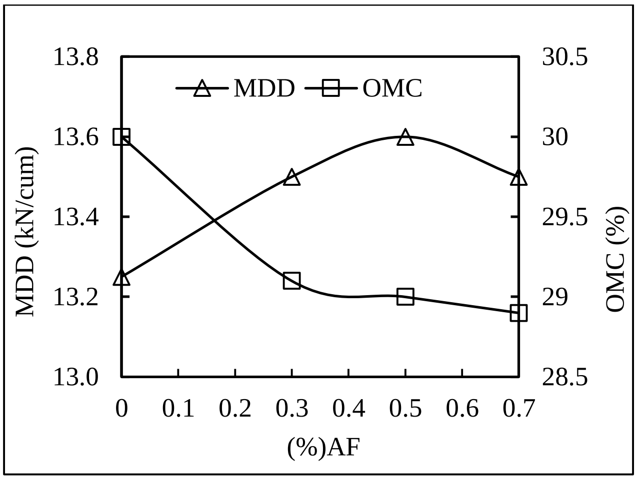

Fig. 8 Variation of MDD and OMC of Soil+6%SF+(%)Areca fiber mix

Figure 8 specifies that the mixture of 6% silica fume with 0.3%, 0.5% and 0.7% areca fiber results in a rise in MDD and a reduction in OMC. In the case of peat-silica fume and areca mixes, a rise in the dosage of silica results in an increase in MDD. Due to a cementitious compound of silica fumes forming a pozzolanic reaction and higher specific gravity, the soil's MDD of these mixes increases with a percentage rise in its content. The silica and alumina particles exhibit natural pozzolanic properties, allowing them to react with calcium ions. This reaction leads to forming C-S-H gel and C-A-S-H gel within the soil structure [13]. This phenomenon is due to the introduction of silica fume, which serves to fill the voids within the porous peat structures, forming the dense matrix. It is accompanied by a decrease in OMC. First, OMC increase with the increase in the dosage of coir due to fiber absorption capacity. However, due to the pretreatment of fiber with linseed oil, its absorption capacity becomes less.

Accompanied by an increase in silica fume dosage, the OMC of this mix samples decreases due to the increase in pozzolanic reaction. Silica fume mixes lead to a rise in MDD and a reduction in OMC. The disparity in specific gravities between peat soil (with a specific gravity, G, of 1.63) and silica fume (with G=2.2) could account for the observed. The incorporation of silica fume with areca fiber into the peat soil appears to impact the compactness and density, contributing to the alteration in MDD and OMC values by increasing in MDD and decreasing in OMC values, signifying higher water absorption capacity of silica fume and an associated rise in optimal moisture content for compaction. These observations offer valuable insights into the utilization of silica fume and areca fiber as stabilizing agents to enhance the strength characteristics of Arunachal Pradesh Peat.

The present research examined the efficacy of silica fume and areca fiber as stabilizers to enhance the strength characteristics of Arunachal Pradesh Peat of Ziro Valley. According to the experimental results, an increase in the percentage of areca fiber in peat-silica increases MDD. The absorption capacity of areca fiber, with its significant porous properties, contributes to the increase in OMC, indicating lesser water content required for compaction.

However, due to the pretreatment of fiber with linseed oil, its absorption capacity becomes less. Simultaneously, there is an increasing trend in MDD, suggesting higher compactness and density of the soil in conjunction with silica fume and areca fiber mixture.

4.4. UCS Value of Peat-Silica Fume Mix

The soil UCS value without any stabilizer mixed after 28 days of curing was determined to be 79 kPa. However, the addition of different percentages of silica fume content (6%, 8%, 10%) resulted in varying UCS values with no curing (0 days) were 107.8 kPa,111kPa and 108kPa for respective silica fume percentages.

Significant improvements in UCS values were observed after 28 days of curing. It is evident from the data that the addition of silica fume content to the peat soil led to a considerable enhancement in the UCS values, both with and without curing. The curing process plays a crucial role in further improving the strength properties of the soil-cement mixes, as reflected in the higher UCS values obtained after the 28-day curing period.

Figure 9 demonstrates the difference in UCS of peat soil stabilized with Silica Fume (SF) over various curing periods. On the other hand, Figure 10 portrays stress-strain curves representing different combinations of Silica fume and soil after a curing duration of 28 days. As shown in Figure 9, there is a noticeable improvement in UCS as the silica fume content rises as a result of the self-hardening characteristic of soil-silica fume blends. It is important to note that the strength development is at a very fast rate during the curing period. The significant increase in strength observed in the soil samples is credited to the combined effects of the pozzolanic activity and the voids filling of silica fume.

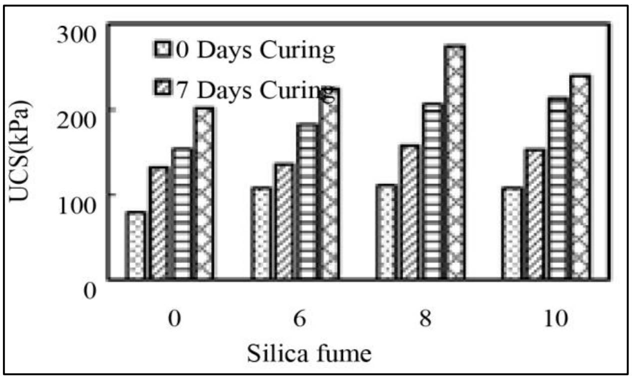

Fig. 9 Variation of UCS of soil and silica fume with respect to change in curing days and percentage of SF.

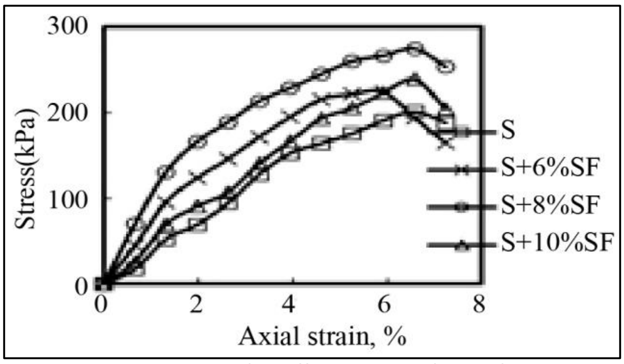

Fig. 10 Stress-strain curve for different mixes of Silica fume with soil at 28 days curing period

This strength improvement is ascribed to the infiltration of calcium ions into the pore water, resulting in the development of hydrate gels [13]. The increase in silica fume enhances pozzolanic particles while reducing CaO particles [9]. These results indicate a substantial development in the soil-silica fume mix strength over the curing period. The stress-strain relationship for soil-SF mixtures indicates that adding SF enhances the soil engineering property, improving its load-bearing capacity and deformation resistance, resulting in higher strain values when subjected to loads. During the curing process, the pozzolanic reaction causes structural changes that may form more rigid and brittle compounds within the soil-SF mix, leading to brittle behavior [12]. The enhancement in the Unconfined Compressive Strength (UCS) results from the creation of cementitious compounds resulting from the interaction of silica found in the soil and the supplementary materials SF [11]. However, the decline in UCS subsequent to the addition of 10% SF might have occurred from an overabundance of SF introduced into the soil, potentially leading to the growth of weaker bonds amid the soil and the cementitious compounds.

Fig. 11 UCS failure pattern of soil-silica fume mix at 28 days curing period

Figure 11 illustrates failure patterns subsequent to 28 days of curing in a material's Unconfined Compressive Strength (UCS) test. The soil mix shows brittle behavior, which may be due to cementitious compounds resulting in the development of strength and stiffness in soil, resulting in the brittleness of the sample.

4.5. Unconfined Compressive Strength (UCS) Value of Peat-Areca Fiber- Mixtures

Areca fiber taken 0.3%,0.5% and 0.7% of soil weight. With varying areca fiber proportions, the UCS values increased with the curing period from 0 to 28 days. Specifically, it elevated from 79 kPa to 324.88 kPa, which was achieved for soil with 0.5% AF at 28 days of curing for fiber contents (highest UCS).

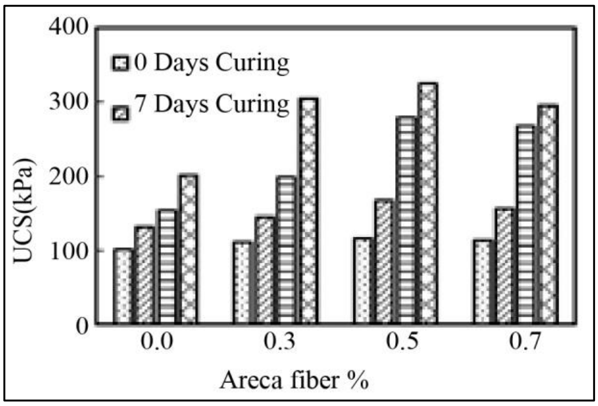

Fig. 12 Variation of UCS of soil and areca fiber with respect to change in curing days and percentage of AF

As revealed by UCS tests, adding areca fibers significantly strengthens the soil as reinforcement. Figure 12 illustrate the variations in UCS with curing time. Adding Areca fiber improves the soil as a reinforcement, along with extended curing time, thus positively influencing the UCS of soil. Figure 12 illustrates the difference in UCS of peat soil stabilized with Areca Fiber (AF) across different curing periods. The observed trend in Figure 14 reveals a significant enhancement in UCS with increasing fiber dosage with an optimum value at 0.5% fiber having a UCS value of 324.8 kPa, particularly with prolonged curing periods. The unreinforced soil sample displayed brittle behaviour after reaching peak stress, with a rapid drop indicating sudden failure. On the other hand, soil samples reinforced with fiber exhibited a more ductile response, where fibers bridged cracks and prevented entire failure after peak stress. Areca fibers contributed to maintaining residual strength post-peak stress, resulting in controlled deformation rather than abrupt failure [3]. This results in decreasing the height of the sample under the UCS test under peak load without sudden failure, sustaining deformation. Higher percentage dosage in soil results in difficulties in the uniform distribution of fiber in the soil. The enhancement in soil cohesion, improved gradation, and the interlocking or compaction of soil have been credited for this improvement.

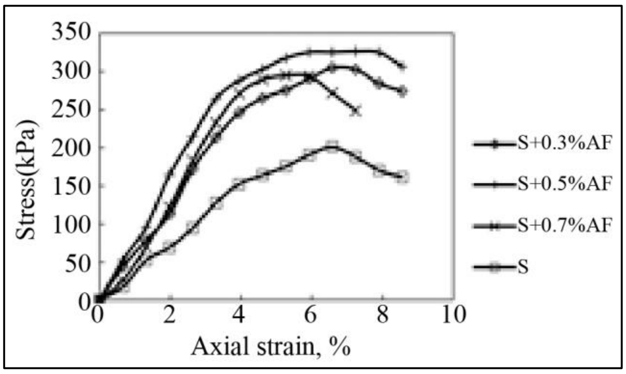

Fig. 13 Stress-strain curve for different mixes of areca fiber with soil at 28 days curing period

Lekha et al. [10] noted a similar outcome when blending areca fiber and cement in laterite soil. Previous studies have also documented comparable enhancements in strength [5, 10]. Meanwhile, Figure 15 depicts stress-strain curves representing various combinations of Areca fiber and soil after a curing duration of 28 days. The unreinforced peat soil sample had an axial strain failure of only 0.039, while the soil reinforced with 0.5% fibers showed a significantly better strain of 0.067 after 28 days. This improvement in strain capacity demonstrates that soil reinforced with fiber can withstand significantly greater deformation before failing than soil without reinforcement.

Figure 16 failure patterns of soil-areca fiber mix in the Unconfined Compressive Strength (UCS) test of a material. When the soil is mixed with areca fiber, soil interlocking or compaction of soil has been improved.

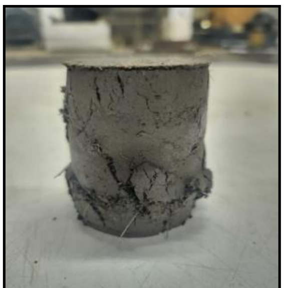

Fig. 14 UCS failure pattern of soil-areca fiber mix at 28 days curing period

During the early stages of curing, the material tends to exhibit ductile behavior as adding areca coir enhances cohesion and stiffness, improving load-bearing capacity and resistance to deformation. This results in higher strain capacity, and plastic behavior under a load of soil reinforced with fiber exhibited a better ductile behaviour, where fibers bridged cracks and prevented total breakdown post-peak stress.

4.6. Investigations on Unconfined Compressive Strength Tests of Peat-Silica Fume-Areca Fiber Mixture

The variations in UCS with curing time of soil-SF%-AF% are depicted in Figures 15, 16 and 17. The addition of both silica fume and areca fiber content, along with extended curing time, positively influenced the UCS of the blends. The UCS value with 6%SF+0.5%AF and 8%SF+0.5%AF shows high UCS values of 346.82 kPa and 369.256 kPa at 28 days curing period, respectively. The UCS values for the S+10SF%+0.5%AF mixtures after 28 days of curing were recorded as 362.48 kPa.

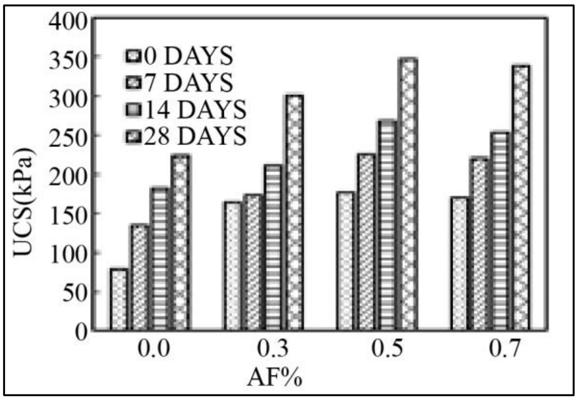

Fig. 15 Variation of UCS of soil and 6% silica fume with respect to change in curing days and percentage of areca fiber

These results illustrate the substantial result of incorporating silica fume and areca fiber in enhancing the strength properties of peat soil, as observed in Figures 15, 16, and 17. The Unconfined Compressive Strength (UCS) of the peat soil treated significantly increased compared to untreated peat soil. This improvement results from C–S–H, C–A–H, and C–A–S–H gels formation between particles of silica fume and soil [2].

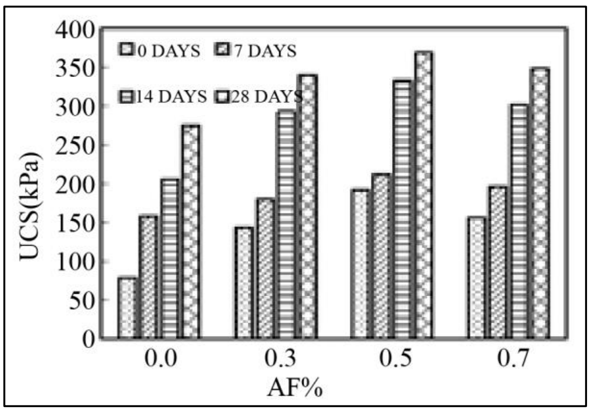

Fig. 16 Variation of UCS of soil and 8%silica fume with respect to change in curing days and percentage of areca fiber

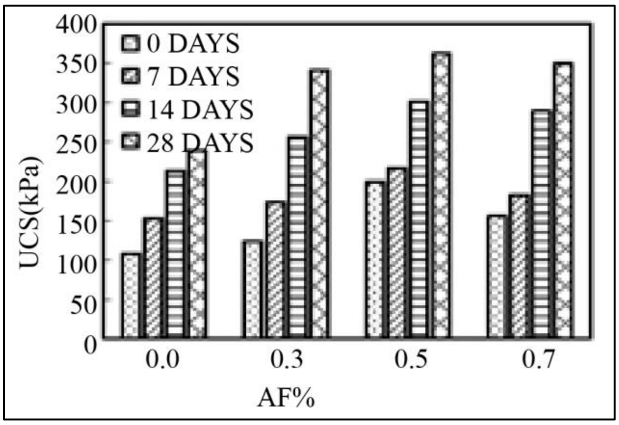

Fig. 17 Variation of UCS of soil and 10%silica fume concerning change in curing days and percentage of areca fiber

These hydrated phases further contribute to the compaction and firming of the soil-cement matrix. Developing these gel phases enhances the interparticle bonding within the soil, improving cohesion and reducing permeability.

Figures 18, 19 and 20 illustrate the stress-strain curve that the mixture of silica fume and areca fiber undergoing 28 days of curing can cause a shift from brittle to ductile failure patterns, causing bulging at the failure of the soil sample. The unreinforced soil sample displayed brittle behaviour, with stress dropping sharply after reaching its peak, leading to sudden failure, while the fiber-reinforced soil demonstrated a more ductile and gradual response. Fibres-reinforced soil prevents sudden cracks and full deterioration post-peak stress [3].

From highest UCS values obtained with 8%SF+0.5%AF obtained a UCS value of 369. 256 kPa at 28 days curing period, which is the optimum value. Soil reinforced with areca fiber samples exhibited a more ductile response, where fibers bridged cracks and prevented complete disintegration after peak stress. These observations are pivotal for comprehending how varying ratios of silica fume and areca fiber impact the strength characteristics of soil mixtures over time. They underscore the potential benefits of combining these additives to achieve superior strength performance, which is valuable for soil stabilization and engineering projects.

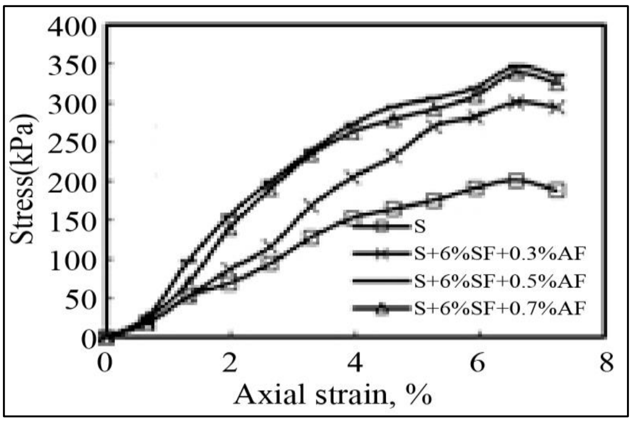

Fig. 18 Stress-strain curve for different mixes of 6% SF and %AF with soil at 28 days curing period

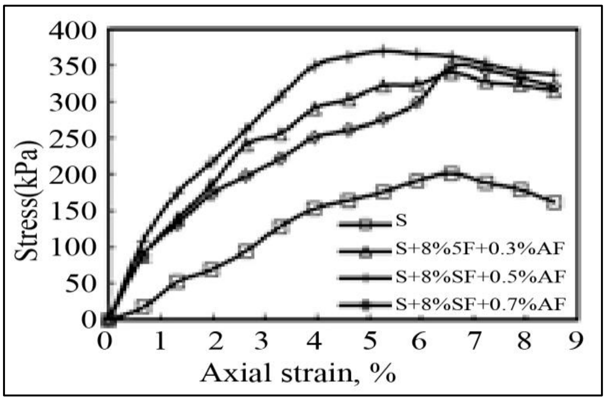

Fig. 19 Stress–strain curve for different mixes of 8% SF and %AF with soil at 28 days curing period

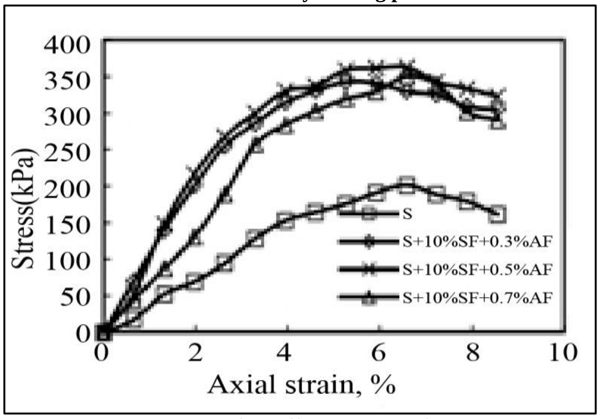

Fig. 20 Stress-strain curve for different mixes of 10% SF with %AF with soil at 28 days curing period

Areca fibers helped maintain residual strength after peak stress, resulting in controlled deformation instead of abrupt failure. This phenomenon is commonly seen in certain types of soils or clayey materials when treated with areca fiber and allowed to cure.

Figure 21 shows the failure pattern of UCS Samples of soil-SF-AF mix and failure pattern at 28 days curing period. This improvement in strain capacity demonstrates that soil reinforced with fiber can endure significantly greater deformation before failing compared to soil without reinforcement.

Fig. 21 UCS Samples of soil-SF-AF mix and failure pattern at 28 days curing period

The results showed a strong association between soil-SF-AF mix content and UCS value, indicating increased soil strength. Mixing peat soil with Silica Fume (SF) and Areca Fiber (AF) leads to more significant improvements in the soil's properties than using either alone. The UCS value with 6%SF+0.5%AF and 8%SF+0.5%AF shows high UCS values of 346.82 kPa and 369.256 kPa at 28 days curing period, respectively. The UCS values for the S+10SF% +0.5%AF mixtures after 28 days of curing were recorded as 362.48 kPa. The highest strength was recorded at the combination of soil with 8%SF+0.5%AF having a UCS value of 369.256. This combination enhances the soil's strength characteristics due to the cementitious properties of Silica fume. At the same time, areca fibers help maintain residual strength after peak stress, resulting in controlled deformation instead of abrupt failure. Soil reinforced with areca fiber can withstand significantly greater deformation before reaching failure than soil without reinforcement. Together, these materials enhance the performance and strength of the stabilized peat soil. These findings underscore the importance of using a blend of silica fume and fiber-reinforced soil for effective soil stabilization and achieving desired improvements in peat soil properties.

4.7. CBR Behavior of Soil-Silica Fume Mixes

The CBR values for untreated peat soil were measured at 3.45% in dry conditions and 2.27% when soaked. Figure 22 illustrates that CBR values enhance with increased silica fume dosage in both soaked and unsoaked conditions. The higher CBR value in the unsoaked condition may be attributed to the existence of forces due to surface tension, which further enhances resistance to penetration. Additionally, SF enhances bonding strength and promotes the formation of cementitious bonds within the soil grains [9], resulting in more strength gain for the soil. These hydrated phases are further attributed to the compaction and strengthening of the soil-cement matrix. Developing these gel phases enhances the interparticle bonding within the soil, improving cohesion and reducing permeability. The improvement observed is attributed to forming specific types of gel structures, namely C–S–H, C–A–H and C–A–S–H, within the soil matrix. These gels are formed due to interactions between particles of silica fume and the constituents present in the soil. These gel formations improve certain soil properties, as discussed in the study [2].

Table 5. CBR of the peat-silica fume mixes

Mix proportion	CBR value% (unsoaked)	CBR Value% (Soaked)	%Increase CBR (soaked)
S	3.4	2.2	-
S+6%SF	5.1	3.2	43.1
S+8%SF	7.2	5.7	151.5
S+10%S	8.4	5.9	162.5

Table 5 displays the percentage increase in CBR (soaked and unsoaked) and values of soil-silica fume mixes. The CBR values for blends of peat and Silica Fume (SF) increase from 2.27 to 5.96. This increase represents a percentage improvement from 43.12% to 162.55%, respectively. These test results agree with the outcomes [11]. Figure 24 shows changes in unsoaked and soaked CBR of soil-silica fume mixtures, showing a rise in CBR values under both conditions, leading to improved soil strength.

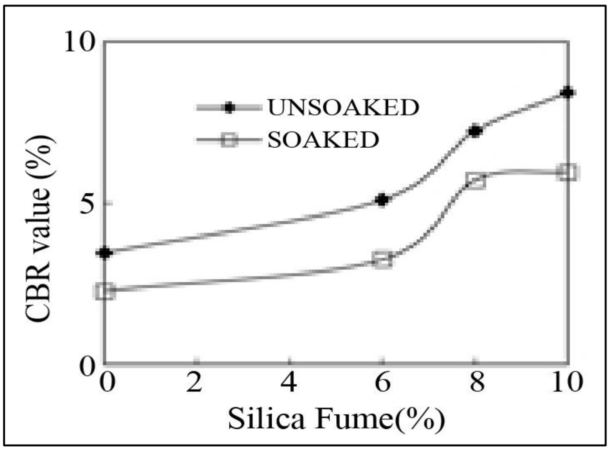

Fig. 22 Variation of unsoaked and soaked CBR of soil-silica fume mixes

4.8. CBR Behavior of Soil-Areca Fiber Mixes

The CBR values of untreated peat soil, both in unsoaked and soaked conditions, were recorded as 3.45% and 2.27%, respectively. Figure 25 shows the development in the CBR value of soil when soil is mixed with areca fiber. The fibrous nature of areca fiber provides additional cohesion and reinforcement inside the soil matrix, resulting in improved resistance to deformation and higher CBR value in both conditions. When incorporated into the peat soil matrix, Areca fibre binds with soil, preventing cracks and voids. This improves stress transmission between soil particles, resulting in greater strength and less crack formation [3].

Table 6. CBR of the peat-areca fiber

Mix Proportion	CBR Value % (Unsoaked)	CBR value % (Soaked)	% Increase CBR (Soaked)
S	3.4	2.2	-
S+0.3%SF	5.7	3.78	66.51
S+0.5%SF	7.13	6.1	168.72
S+0.7%S	8.82	6.6	190.74

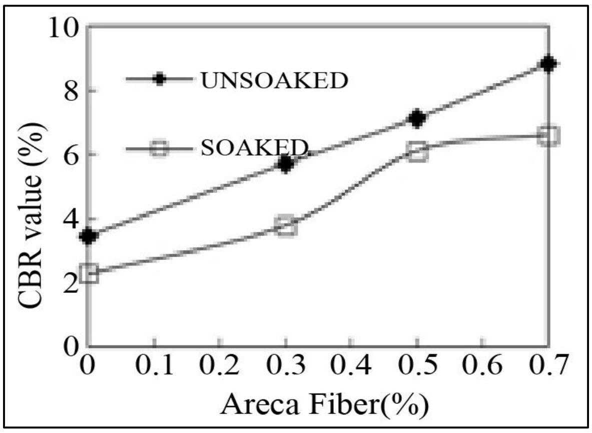

Fig. 23 Variation of unsoaked and soaked CBR of soil-areca fiber mixes

However, soil lost strength in soaked conditions and showed less resistance to plunger penetration. Table 6 illustrates the increase in soaked CBR values of soil-Areca fiber mixtures, ranging from 2.27% to 6.6%, percentage improvement of 190.74%. This finding recommends that the combination of areca fiber positively influences the California Bearing Ratio of the soil. Such a rise in CBR values indicates an enhancement in the load-bearing capacity and overall stability of the peat soil when treated with areca coir.

These results hold significance for geotechnical engineering applications, particularly in projects involving soil stabilization.

4.9. Impact of Silica Fume and Areca Fiber on CBR Behavior of Peat Soil

To assess the effect of silica fume and areca fiber on the strength characteristics of peat soil, test specimens were formulated by combining varying dosages of silica fume (6, 8, and 10) with different percentages of areca fiber (0.3%, 0.5%, and 0.7%).

Table 7 depicts the consequential enhancement in CBR strength by incorporating silica fume and areca fiber into the peat soil.

Table 7. CBR values of the peat-silica fume-areca fiber

Mix Proportion	CBR Value % (Unsoaked)	CBR value % (Soaked)	%Increase CBR (soaked)
S	3.45	2.27	-
S+6%SF+ 0.3%AF	5.7	4.1	80.61
S+6%SF+ 0.5%AF	8.12	6.78	198.67
S+6%SF+ 0.7%AF	8.83	6.84	201.32
S+8%SF+ 0.3%AF	7.51	5.91	160.35
S+8%SF+ 0.5%AF	9.57	6.13	170.04
S+8%SF+ 0.7%AF	7.59	5.43	139.20
S+10%SF +0.3%AF	10.17	6.91	204.40
S+10%SF +0.5%AF	13.71	11.1	388.98
S+10%SF +0.7%AF	11.67	8.9	292.07

Figures 24 and 25 show the results demonstrating a notable improvement in CBR values reaching optimum suitable for design objectives for both soaked and unsoaked conditions. Table 7 displays the CBR values of peat-silica fume-areca fiber mixtures and the percentage increase in CBR. CBR values increased from 3.45 to 11.67 percent for unsoaked conditions and 2.27 to 8.9 percent for soaked conditions, with a percentage improvement of 292.07%.

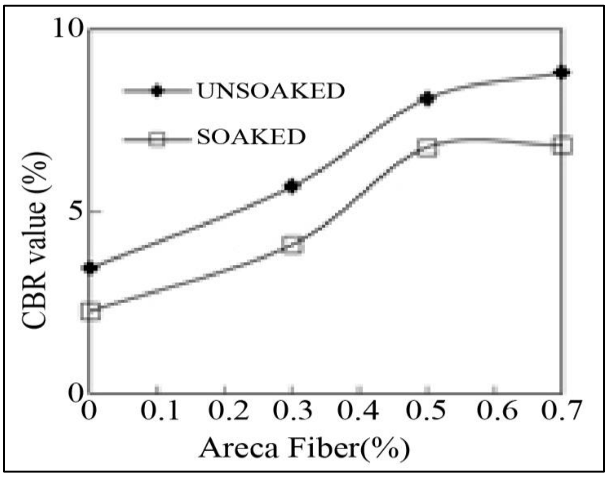

Fig. 24 Variation of unsoaked and soaked CBR for different mixes of 6% SF with soil

However, it is observed that further increments in the percentage of silica fume and areca fiber beyond a certain threshold may not yield significant additional benefits. Higher dosages of silica fume may affect safety concerns. On the other hand, a higher dosage of areca coir beyond 0.5% leads to a problem related to its uniform distribution throughout the soil. Remarkably, the mixture denoted as S+10SF+0.5AF exhibits the most substantial enhancement in CBR, registering values of 13.71 for unsoaked and 11.1 for soaked conditions.

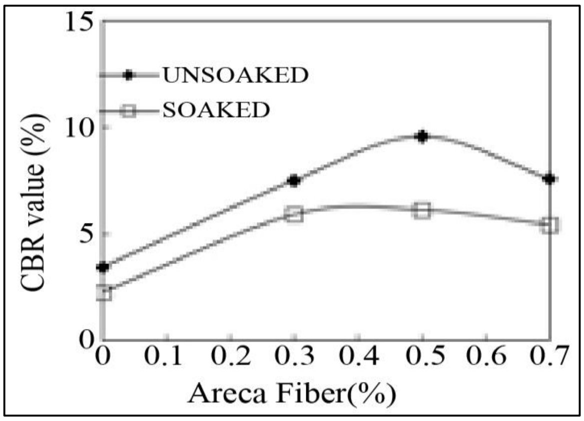

Fig. 25 Variation of unsoaked and soaked CBR for different mixes of 8% SF with soil

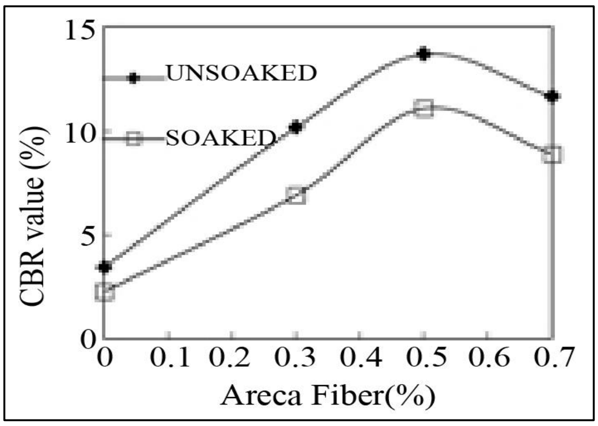

Fig. 26 Variation of unsoaked and soaked CBR for different mixes of 10% SF with soil

According to IRC: SP-72-2015, the subgrade strength to design must be at least 5% (classified as fair), even for low-traffic conditions. Stabilization is required to ensure a minimum % design CBR of 5% if the subgrade soil's CBR drops below 5%. The strength of the subgrade is separated into the following classes.

Soil led to better CBR values in both unsoaked and soaked conditions. Notably, adding silica fume substantially increased the CBR values from 43.12% to 162.55%.

Furthermore, incorporating areca fiber further enhanced the CBR. According to the guidelines outlined in IRC: SP-72-2015, the CBR value achieved at the optimized silica fume dosage and areca fiber percentage is classified as "very good" for construction purposes as a result obtained in Table 8 having the combination of S+10%SF+0.5%AF.

Consequently, any further escalation in silica fume dosage and areca fiber percentage would result in inefficient and uneconomical resource utilization without proportionate improvements in CBR values. These findings underscore the importance of meticulous optimization in selecting silica fume dosage and areca fiber concentration to achieve optimal soil stabilization outcomes, thereby minimizing material wastage and ensuring cost-effective construction practices.

Table 8. Quality of Class Subgrade Range (CBR%) (source: IRC: SP-72-2015)

Very Poor	SI	2	Very Poor	SI
Poor	S2	3 to 4	Poor	S2
Fair	S3	5 to 6	Fair	S3
Good	S4	7 to 9	Good	S4
Very Good	S5	10 to 15	Very Good	S5

The study investigated how Silica Fume (SF) and Areca Fiber (AF) affects the CBR values of peat soil. The findings indicated that increasing the silica fume in peat values from 66.51% to 190.74%. Adding 10% silica fume with 0.5% areca fiber to the peat soil mix resulted in CBR values that met design requirements as per IRC: SP-72-2015 for subgrade design. The S+10SF%+0.5%AF mixture showed the most significant improvement, boosting the CBR values from 3.45% to 13.71% in unsoaked conditions and from 2.27% to 11.1% in soaked conditions, representing a 388.98% increase compared to the untreated peat soil. Based on these results, the study recommends using S+10%SF+0.5%AF mixtures for treating subgrade soils, as these combinations significantly improve CBR values, indicating enhanced strength and load-bearing capacity. Utilizing these stabilizers can effectively improve subgrade performance, aiding the successful construction of infrastructure projects.

4.10. SEM Image of Peat Soil

SEM (Scanning Electron Microscope) images were taken to examine the morphology of both the original peat soil and several treated peat soil samples. These micrographs, depicted in Figure 27, offer valuable insights into the physical attributes of the peat soil. Figure 27 provides a detailed view of the peat sample, showing decomposed fibers that indicate its fibrous nature. It illustrates that untreated peat soil consists of fibrous woody and porous material. This decomposition suggests significant degradation and change over time. It showcases visible voids within the peat microstructure, attributed to its organic composition, which mainly comprises plant debris and organic matter. These voids form due to decomposition and decay processes. SEM analysis of the untreated, dry peat sample unveils its intricate fiber arrangement, presence of voids, and overall porous nature, crucial for understanding its geotechnical behavior and engineering applications.

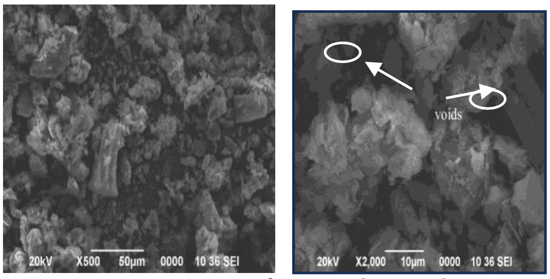

Fig. 27 SEM images of untreated peat soil

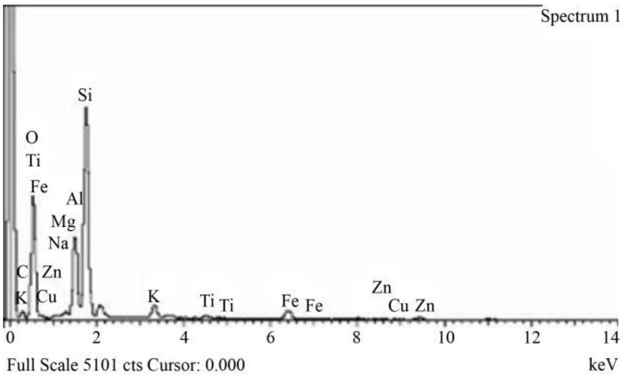

Fig. 28 EDX result of untreated peat soil

It's worth noting that this analysis establishes a foundational understanding, with potential for further exploration as a result of treatments or stabilizers on the microstructure and stability of peat soil.

4.11. SEM Image of Silica Fume

SEM image silica fume as depicted in Figure 31.

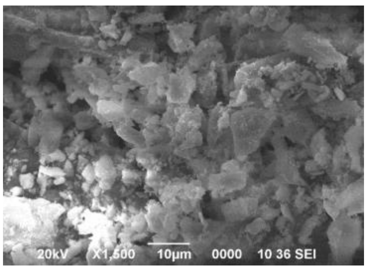

Fig. 29 SEM images of silica fume

Shows the arrangement of its particles, which are more densely packed. Thus, it helps in the stabilization of soil by transforming soil particles to shift from dispersed to a flocculated structure, forming cement-like compounds.[14].

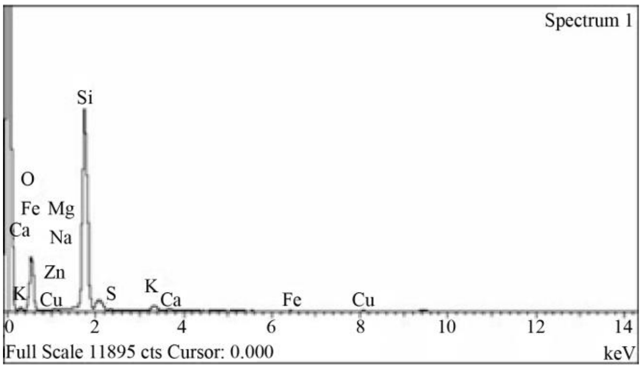

Fig. 30 EDX result of silica fume

4.12. SEM Image of Areca Fiber

Scanning Electron Microscopy (SEM) was performed to analyze the microstructure of Areca Fiber (AF), with the resulting micrographs shown in Figure 31.

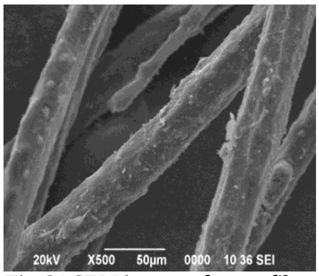

Fig. 31 SEM images of areca fiber

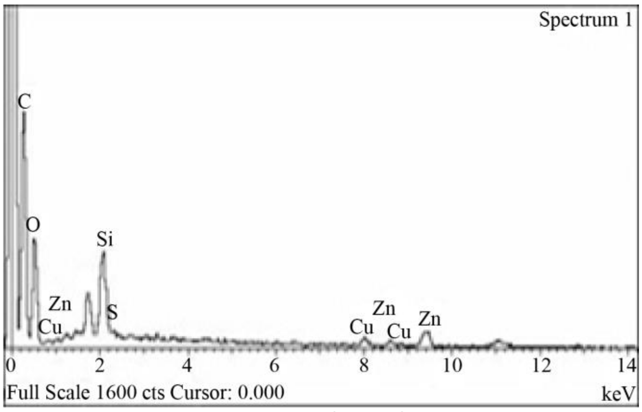

Fig. 32 EDX result of areca fiber

These SEM images offer a better understanding of the morphology and composition of areca fiber. SEM investigation exposed the rough textured surface of the areca fibers, which plays a pivotal role in enhancing strength, attributed to the observed interfacial interaction between the fibers and the soil to be mixed, as evidenced by the SEM [14].

This contributes to maintaining residual strength post-peak stress, resulting in controlled deformation rather than abrupt failure [3]. Fiber-reinforced soil showed a more ductile behaviour, with fibres bridging cracks and preventing total breakdown after reaching peak stress.

4.13. SEM Image of Soil-Silica Fume Mix

Figure 33 depicts an SEM image of treated peat soil with silica fume after 28 days of curing. The chemical reaction causes the soil particles to shift from a porous state to a more flocculated form.

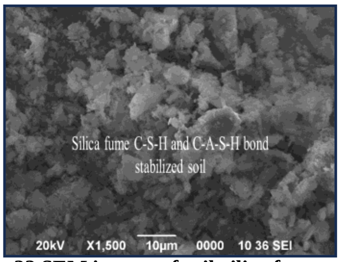

Fig. 33 SEM images of soil-silica fume mix

This transition is clearly portrayed in the SEM of treated peat soil, which also reveals the existence of binding particles surrounding the soil particles. The agglomeration observed in these SEM images is primarily due to the chemical reaction occurring in the existence of water within the voids. This reaction leads to the development of C–S–H gel and C–A–S–H gel within the soil matrix [13]. C–S–H, C–A–H and C–A–S–H are crucial hydration products in cement. C–S–H provides concrete strength, C–A–H contributes to early strength and rapid setting, and C–A–S–H enhances strength, durability, and chemical resistance in blended types of cement.

This phenomenon alters the soil's physical properties, enhancing its stability and structure. A substantial amount of soil particles were coated with silica fume, effectively filling the micropores. Upon examination of the image, it becomes evident that the voids within the soil particles are diminished [13]. Furthermore, the observation reveals a significantly denser matrix characterized by a pore reduction, indicating a continuous mass of the treated soil. This densification contributes to enhancing the properties of the sample.

4.14. SEM Image of Soil-Areca Fiber Mix

Figure 34 depicts an SEM image of treated peat soil with silica fume after curing for 28 days. The transformation of the soil matrix from a porous to a more flocculant state is due to a chemical reaction. The connection between the soil and the fiber is evident, with the rough texture of the areca fibers promoting resistance between soil grains through interfacial interactions [14]. This phenomenon contributes to the strength enhancement observed in stabilized soil by incorporating fiber.

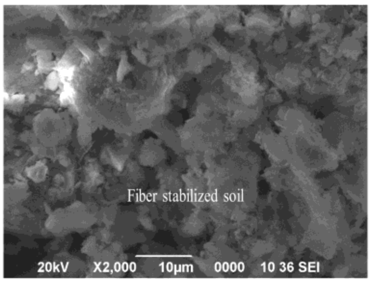

Fig. 34 SEM images of soil-areca fiber mix

Additionally, the formation of a denser microstructure was evident from the SEM image, which was increasing. Notably, the areca fibers remain unbroken even after specimen failure occurs.

4.15. SEM of Soil-Silica Fume-Areca Fiber Mix

Figures 35(a) and 35(b) depict the SEM image of the soil-silica fume and areca fiber mix. Silica fume forms agglomeration with soil particles to form more denser soil. Areca fiber, due to its rough surface texture, holds peat soil, forming a dense matrix and thus fills the gaps between the soil voids, hence strengthening the soil.

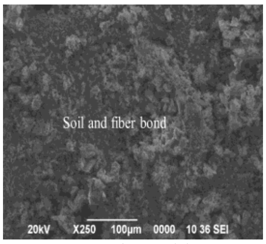

Fig. 35(a)

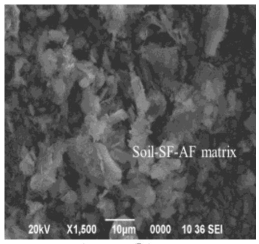

Fig. 35(b)

The fiber inclusion enhances the strength of SF-stabilized soil. Moreover, the curing process leads to the growth of cementitious compounds, resulting in a denser microstructure and improved resistance between the fibers and hydration products [15].

5. Conclusion

The current study observed the efficiency of silica fume and areca fiber as stabilizers in improving the properties of peat soil. Using silica fume and areca fiber in soil stabilization enhances durability, optimizes performance, and provides a cost-effective, sustainable construction solution.

From the experimental findings, subsequent inference can be drawn: MDD of peat soil sample rises as silica fume content rises in soil due to its higher specific gravity value than soil, while OMC of soil decreases due to *pozzolanic* reaction of silica fume. Areca fiber decreases MDD and increases OMC due to its lightweight properties and ability to absorb water. However, increasing the silica fume and areca fiber proportion in peat-SF-AF mixes decreases the OMC and increases the MDD, giving more strength to the soil when the SF and AF content is increased. This may be due to increased SF cementitious content and linseed oil applied on areca fiber for treatment as the AF percentage increases, decreasing water absorption.

The study shows the S+8%SF+0.5%AF mixture demonstrated the highest UCS values of 369.256 kPa among the tested combinations for 28 days of curing, indicating its effectiveness in improving the strength of peat soil. Soil undergoes brittle to ductile failure in the presence of areca fiber in the soil. The fiber-reinforced soil also sustains peak load without undergoing abrupt failure. CBR Values in both unsoaked and soaked conditions improved as the amount of silica fume and areca fiber in the soil mix increased. The CBR value of the S+10SF mix significantly improved from

3.45% to 8.41% (unsoaked) and from 2.27% to 5.96% (soaked), reflecting a 162.55% increase. The CBR value of the S+0.7%AF mix significantly improved from 3.45% to 8.82% (unsoaked) and from 2.27% to 6.6% (soaked), reflecting a 190.74% increase. The S+10SF%+0.5%AF mixture showed the most significant improvement, with CBR values increasing from 3.45% to 13.71% (unsoaked) and from 2.27% to 11.1% (soaked), a 388.98% increase compared to the untreated peat soil. Using S+10%SF+0.5%AF mixtures thus meets the design requirements recommended for treating subgrade soils. The optimum amalgamation of silica fume and areca fiber content may vary depending on specific soil characteristics and project requirements. SEM images show the fibrous nature of peat soil with large voids. However, these voids were reduced after the inclusion of silica fume, having a denser matrix and areca fiber, which has rough morphology, forming a denser matrix of soil-mix.

Author Contribution

Dr. Ajanta Kalita, an Assistant Professor and co-author, was instrumental in directing the experimental examination and X-ray diffraction examination. She also played a key role in reviewing the manuscript in detail.

Data Availability Statement

The data collected and analyzed in this study can be provided upon practical request from the corresponding author.

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