

## ECO-FRIENDLY STABILIZATION OF BABOLSAR COASTAL SAND USING CEMENT, AGRICULTURAL WASTE ASH AND CARBON FIBERS

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### ABSTRACT:

Sandy soils in coastal regions often exhibit low strength and instability, posing challenges for geotechnical applications. This study examines the combined influence of cement, carbon fibers, and rice husk ash (RHA) on the shear strength of sand from the Babolsar coastline. Specimens were prepared with varying cement contents (1–2%), RHA proportions (3–7%), and fixed carbon fiber dosages (0.1% and 0.15%), then tested under direct shear after different curing periods. The mixture containing 2% cement, 7% RHA, and 0.15% carbon fiber displayed the highest strength, with an internal friction angle of 30.81° and cohesion of 0.17 kg/cm<sup>2</sup> after 7 days. Strength gains persisted over time, with friction angle increases of 3.45–13.25% and cohesion gains of up to 9.52% compared to day 1. Microstructural analyses using XRD and SEM revealed the formation of C–S–H, calcite, and crystal-line silica, alongside dense packing, uniform fiber dispersion, and reduced porosity. These findings confirm that incorporating cement, RHA, and carbon fibers can synergistically enhance coastal sand stability, offering a sustainable and cost-effective improvement method for short-term engineering applications

**Keywords:** Soil stabilization, carbon fibers, cement, liquefaction, coastal sand, rice husk ash.

### INTRODUCTION

Rapid population growth and urban development in coastal and earthquake-prone areas have increased the demand for efficient use of soil resources for infrastructure construction. Sandy soils, particularly along the Caspian Sea coast, pose significant challenges in geotechnical engineering due to low water retention capacity and high liquefaction potential under dynamic loads such as earthquakes. Liquefaction, caused by sudden stress changes in saturated sandy soils, can severely reduce bearing capacity and lead to structural failure, and this problem is particularly pronounced in the silica-rich soils of the Caspian coast, which exhibit low density and high friction angles. To address these challenges, recent studies have explored various soil stabilization techniques, highlighting both the potential and limitations of different additives. While the addition of cement has long been recognized for enhancing soil strength and durability (Dehghanbanadaki et al., 2022; Raftari et al., 2024), emerging materials such as rice husk ash (RHA) and carbon fibers (CF) offer supplementary mechanisms that have been less systematically investigated in coastal sandy soils.

To improve the mechanical properties of these soils, various methods have been proposed, including the addition of cement, carbon fibers, and rice husk ash (RHA), which enhance soil resistance to liquefaction and increase load-bearing capacity by altering its physical and chemical characteristics. However, many previous studies have focused on either cementitious or fiber-based stabilization separately, and the synergistic effects of combining RHA and CF with low cement dosages remain underexplored.

The stabilization of sandy soils can be effectively enhanced through the use of rice husk ash (RHA) and carbon fibers (CF), which contribute to mechanical performance via distinct mechanisms. RHA is primarily composed

of amorphous silica and participates in pozzolanic or geopolymeric reactions by reacting with calcium hydroxide produced during cement hydration, forming additional calcium silicate hydrate (C-S-H) and aluminosilicate gels. These reactions densify the soil matrix, increase particle bonding, and consequently improve both compressive strength and stiffness. Carbon fibers, on the other hand, function as reinforcing agents by bridging developing cracks, transferring stress from weaker soil regions to the fibers, and enhancing the ductility of the stabilized soil. The crack-bridging mechanism slows crack propagation, increasing post-cracking strength, while stress transfer promotes a more uniform distribution of internal forces and reduces the likelihood of sudden brittle failure. Increased ductility allows the soil to undergo greater deformation before failure, improving its energy absorption capacity. The combined use of RHA and CF can thus produce synergistic effects, simultaneously enhancing strength, toughness, and deformation capacity, providing a scientifically justified basis for their incorporation in soil stabilization studies. Rice husk ash, a widely available industrial byproduct in northern Iran, contains 85–95% amorphous silica and acts as an active pozzolanic material, serving as an effective partial substitute for cement while reducing the environmental impact of cement production. Although considerable progress has been made in using nanofibers and natural materials for soil stabilization, limited research has addressed their application in sandy soils under varying stress and moisture conditions.

Cement is one of the most widely used stabilizing agents for enhancing the strength and durability of soft and loose soils due to its high binding capacity and long-term performance (Dehghanbanadaki et al, 2022; Raftari et al., 2024). Over the past decades, numerous studies have explored the behavior of Caspian Sea coastal sands stabilized with cement, carbon fibers, and RHA. Riahi

Dehkordi et al. (2021) investigated the effect of a geopolymer based on rice husk ash (RHA) and iron ore tailings on the stabilization of sandy soil. Their results showed that adding 10% RHA and up to 24% iron ore tailings with a sodium hydroxide solution significantly increased the unconfined compressive strength (UCS) of the treated samples at all curing periods. For samples containing calcium carbide residue (CCR), increasing the tailings content up to 18% enhanced UCS up to 28 days of curing, and the optimum CCR dosage as an alkaline activator was determined to be 7%. Under these conditions, the UCS of the selected geopolymer-stabilized samples at 7, 28, and 90 days of curing was 8.9, 4.7, and 25.5 times higher than the control soil, respectively.

Haqbin and Adhami (2021) reported that a mixture of 6% lime, carbon fibers, and 4% nanosilica improved shear strength and permeability in clayey soils. They found that CF alone had a minor or variable effect on soil shear strength, but when combined with lime and nanosilica, they significantly improved mechanical performance. CF were applied at percentages up to 2% and enhanced soil behavior through crack bridging, stress transfer, and increased ductility. Faktor Sakhi and Ebrahimi (2022) demonstrated that agricultural waste ashes, including bagasse (117%), rice husk (89%), and almond (80%), enhanced uniaxial strength in fine-grained soils. Kiani Nejad et al. (2023) studied the stabilization of wind-blown sands using a small amount of metakaolin (6%) and calcium carbide residue (CCR, 8%) as an alkaline activator. Even at these low dosages, the unconfined compressive strength and failure strain of the soil improved significantly, with most strength gain occurring within the first 28 days of curing. Higher CCR doses negatively affected the gel matrix, confirming that the observed improvements are achieved with minimal additive content. This study highlights the effectiveness of small amounts of alkaline-activated metakaolin and CCR for enhancing soil mechanical behavior while reducing environmental concerns. Ebrahimi Lakmeh et al. (2023) investigated the laboratory optimization of Babolsar coastal sand stabilization using cement, marble powder, and cellulose fibers. Small amounts of these additives, ranging from 1–7% for cement and marble powder and up to 1% for cellulose fibers, were incorporated into the soil. The study demonstrated that even at these low dosages, the mechanical properties of the sand, including density and shear strength, were significantly improved. This highlights the effectiveness of minimal additive content for enhancing coastal sand performance. Bahrami et al. (2025) investigated the stabilization of coastal sandy soils using small amounts of cement and nanosilica. Even at low dosages, the additives significantly reduced total displacement from 1.86 to 0.41 mm and final strain from 55.6% to 11.1%, while slightly increasing ultimate stress from 114.5 to 120.7 kPa. These results demonstrate that minimal additive content can effectively enhance soil mechanical performance. Elyaslankaran et al. (2021) evaluated the effects of lime and rice husk ash (RHA) on the behavior of coastal soils. The study showed that a small addition of lime and RHA in a 1:2 ratio (8% lime) significantly increased shear stress under a normal stress of 200 kPa. Cohesion and internal friction angle were also notably improved, with cohesion increasing up to 28% after 90 days of curing compared to 7 days. These results indicate that even minimal additive content can effectively enhance the shear strength of sandy coastal soils.

Vafaei et al. (2022) showed that adding small amounts of hemp fibers (0.3–0.9% by weight, 6–14 mm) significantly improved shear strength, cohesion, and internal friction of coastal sandy soils, with shear strength increases up to 845%. This demonstrates that minimal natural fiber content can effectively enhance soil mechanical performance. Xiao et al. (2022) investigated the effect of rice husk ash (RHA) and polypropylene fibers on cement-stabilized soils. Fiber contents of 0.3–0.5% were found to be most effective, significantly enhancing unconfined compressive strength (UCS) and split tensile strength (STS). RHA improved UCS in SC and CLS soils and STS in all soil types, while polypropylene fibers mainly enhanced UCS in CL soils. These results indicate that small additive dosages can effectively strengthen cement-stabilized soils. Owino et al. (2022) studied the effect of basalt fiber dimensions on RHA- and cement-stabilized soils. Fibers of 3–12 mm, combined with 3% cement and 5% RHA, improved compressibility and swelling resistance. The best performance was observed for 12 mm fibers, indicating that small fiber dosages can effectively enhance soil consolidation and dimensional stability. Zhao et al. (2023) showed that increasing mortar strength enhanced dynamic compressive resistance and energy storage in composite mortar-rock materials. Nepal et al. (2023) reported that colloidal silica and polymer grouts effectively reduced permeability and improved soil strength. Majia et al. (2023) observed that silica from RHA increased the elastic modulus of fiber cement by up to 9.4%. Magoswari et al. (2023) found that 10% RHA and 0.75% gypsum fibers improved both soil strength and permeability. Li et al. (2025) demonstrated that alkaline-activated RHA and polypropylene fibers enhanced mechanical properties and slope erosion resistance. Finally, Aref and Hossein (2025) reported that a mixture of 6% RHA and 6% cement increased subgrade bearing capacity to 21.3 kPa. Previous studies have consistently demonstrated that the use of relatively small amounts of stabilizing additives can lead to substantial improvements in the unconfined compressive strength, indirect tensile strength, cohesion, and internal friction angle of sandy soils. These findings indicate that even low percentages of cementitious, pozzolanic, or fibrous additives, when appropriately selected and proportioned, are capable of significantly modifying the mechanical response of soil while remaining economically viable.

However, a critical review of the existing literature reveals that a large proportion of published studies have focused either on the isolated use of cementitious or pozzolanic materials or on fiber reinforcement applied independently. Moreover, many investigations have relied on relatively high additive contents, which limits the practical applicability of their findings in real-world geotechnical projects. In contrast, systematic and comprehensive studies addressing the combined use of agricultural waste-derived pozzolanic materials and reinforcing fibers in coastal sandy soils—particularly at low and practically feasible dosages—remain scarce. In addition, although carbon fibers have attracted attention due to their superior mechanical properties, their application in soil stabilization has not yet been extensively investigated. This limitation is largely attributed to economic considerations and the lack of sufficient experimental data regarding their performance when used in combination with cementitious or pozzolanic binders at low contents. Furthermore, many previous studies have primarily emphasized compressive strength parameters, while the shear behavior of soils—particularly variations in cohesion and internal friction angle, which play a critical role in geotechnical design—has received comparatively limited focused attention.

Accordingly, the present study is designed to investigate the combined effects of rice husk ash and carbon fibers, in the presence of small amounts of cement, on the mechanical behavior of Babolsar coastal sand. The primary novelty of this research lies in the simultaneous use of a sustainable pozzolanic material and carbon fibers at low dosages, together with a quantitative evaluation of their influence on the shear strength parameters of coastal sandy soil. This approach is intended to address an existing gap in the literature related to the economical and low-additive stabilization of coastal sands.

## **MATERIALS**

### **2.1. Sample**

Sand samples were obtained from the Babolsar coast on the southern shore of the Caspian Sea, chosen for its extensive sandy beaches and the geotechnical relevance of its soils (Figure 1). The samples were transported to the laboratory, air-dried at room temperature, and sieved through a No. 4 (4.75 mm) mesh to remove coarse particles. Physical properties and grain-size distribution were determined in accordance with ASTM D6913 for accurate classification and grading. The sand is relatively clean, with low cohesion and minimal fines, making it well-suited for evaluating the effects of stabilization additives.



**Figure 1: Location of sand sample collection from Babolsar**

## 2.2. Carbon Fibers

Carbon fibers are thin, lightweight filaments primarily composed of carbon, produced through the thermal treatment of organic precursors such as polyacrylonitrile. Owing to their high tensile strength, high modulus of elasticity, chemical stability, low density, and corrosion resistance, they are extensively used in aerospace, automotive, civil, and geotechnical engineering. In granular soil stabilization, the inclusion of carbon fibers enhances shear strength, reduces settlement, and improves resistance to liquefaction by forming a three-dimensional reinforcing network that distributes stresses and minimizes stress concentration. In this study, 3 mm carbon fibers (Type 3) supplied by Nano Nakh and Gravel Sirjan were incorporated into coastal sand to assess their effects on compressive strength, cohesion, and internal friction angle. The physical and chemical properties of the fibers are detailed in the Materials and Methods section, and Figure 2 presents the carbon fibers used in this study.



**Figure 2: Carbon fibers used in the present study**

**Table 1: Properties of the carbon fibers used in the present study**

Property	Amount	Applicable standard
Density (g/cm <sup>3</sup> )	1.78	ISO 10119-A
Diameter (μm)	6.80	ISO 11567-A
Weight percentage of coating materials	1.5	
Carbon content (weight %)	> 94	
Specific length	3-6-10-12-20	
Package weight (kg)	15	

### 2.3. Cement

In this study, Type II Portland cement, supplied by Neka Cement Factory (Mazandaran, Iran), was employed as the primary binder. Type II cement is particularly suitable for soil stabilization in wet environments susceptible to sulfate attack due to its moderate sulfate resistance and lower heat of hydration compared to Type I. When incorporated into the soil matrix, cement hydrates to form cementitious compounds that fill voids, enhance interparticle bonding, increase strength, and reduce permeability. The cement content in all mixtures was calculated as a percentage of the soil's dry weight.

### 2.4. Rice Husk Ash (RHA)

Rice husk ash (RHA) is a byproduct of rice husk combustion with high amorphous silica content. Due to its pozzolanic properties, RHA reacts in the presence of moisture and calcium to form products such as C-S-H, which enhance soil strength and stability. In this study, RHA was obtained from a factory in Rasht and, after sieving, was added to the sand as a pozzolanic supplement along with cement and carbon fibers. In addition to improving geotechnical properties, the use of RHA contributes to environmental sustainability by recycling agricultural waste. The technical and chemical properties of RHA are presented in Tables 2 and 3.

**Table 2: Technical properties of the rice husk ash used in the present study**

Color	Gray
Specific gravity	2.5-53
Specific surface area	40-100 m <sup>2</sup> per gram
Bulk density	200-300 kg per cubic meter

**Table 3: Chemical properties of the rice husk ash used in the present study**

Property	Value
SiO <sub>2</sub>	86-78
AL <sub>2</sub> O <sub>3</sub>	1-2
Fe <sub>2</sub> O <sub>3</sub>	85-1.16
CaO	81-4.55
MgO	5-4.35
SO <sub>3</sub>	18-1.24
Na <sub>2</sub> O	1-1.14
K <sub>2</sub> O	68-3.54
Heat loss	8-4.55

## EXPERIMENTAL TESTS

### 3.1. Grain Size Analysis

Grain size analysis was conducted according to ASTM D6913 to determine the particle size distribution of the sand. The results, presented as a grain size curve (Figure 5), indicated that the sand falls under the SP category (poorly graded sand) according to the USCS system, consisting of relatively uniform particles with negligible fines. This sand, with high permeability, zero cohesion, and stable granular behavior, is suitable for evaluating the effects of geopolymers and other additives. Physical properties, such as specific gravity and natural moisture content, were also measured to ensure material uniformity. SP sand was selected due to its accessibility, stability, and controllability under laboratory conditions.



### 3.6. Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) was employed to investigate the microstructure and particle distribution of natural sand, rice husk ash, and stabilized samples containing cement and carbon fibers. Samples were dried, ground, and coated with a conductive layer of gold or carbon, then imaged under high-vacuum conditions according to ASTM E1508, ensuring reproducibility and reliable microstructural observations.

## RESULTS

This study aimed to investigate the effects of additives (cement, carbon fibers, and rice husk ash) and their combinations on the geotechnical properties of sand, particularly its mechanical strength and microstructure. Initially, grain size analysis was performed for precise classification of the samples. The standard compaction test evaluated the effect of additives on maximum dry density and optimum moisture content. Direct shear tests assessed shear strength, XRD analyzed crystalline structure and phase changes, and SEM images were used to observe particle and fiber distribution. The results were presented through numerical data, graphs, and analytical images to analyze the effects of stabilizers on the mechanical and structural behavior of the sand.

### 4.1. Soil Compaction Test Results

Standard Proctor compaction tests were performed on Babolsar coastal sand in accordance with ASTM D698 to determine the maximum dry density and optimum moisture content, thereby establishing the relationship between moisture content and dry density. This test is critical in civil engineering applications such as road construction and dam projects, as it helps optimize soil bearing capacity, minimize settlement, and enhance overall stability. For the untreated sand, the maximum dry density was measured at  $1.74 \text{ g/cm}^3$  and the optimum moisture content at 6%, indicating good compaction potential and a relatively high moisture requirement, likely due to the presence of fine particles and the soil's water absorption characteristics. These baseline values were later compared with those of samples stabilized using cement, rice husk ash (RHA), and carbon fibers, as illustrated in Figure 6.

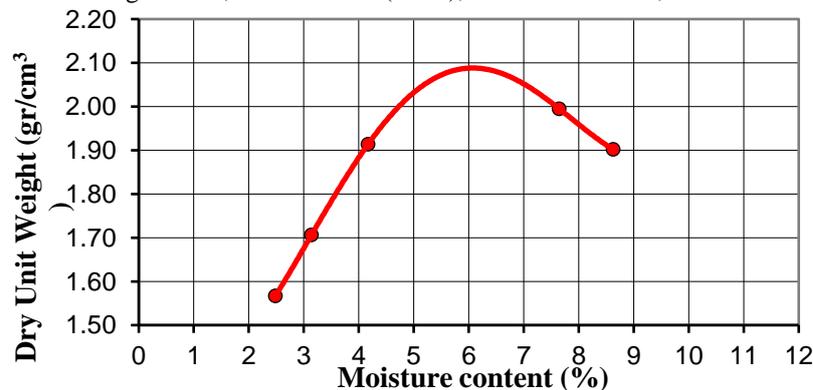


Figure 4: Soil compaction test

### 4.2. Direct Shear Test Results

Direct shear tests were performed to examine the shear behavior of Babolsar coastal sand with the addition of 1%, 1.5%, and 2% cement by dry weight. Following mixing with dry cement, the samples were adjusted to the optimum moisture content (obtained from the standard compaction test), cured under controlled conditions, and tested under three vertical stress levels with three replicates. The untreated sand (control) exhibited an internal friction angle of  $31.91^\circ$  with zero cohesion. Incorporating 1% cement slightly increased the friction angle to  $32.11^\circ$  with negligible cohesion, 1.5% cement resulted in  $32.21^\circ$  and 0.01 kPa cohesion, and 2% cement yielded  $32.31^\circ$  with 0.02 kPa cohesion. These results indicate that the low cement dosages produced only minor improvements in friction angle, primarily due to enhanced grain interlocking and the formation of limited cementitious bonds, while cohesion remained minimal. The limited effect is attributed to the coarse-grained nature of the sand and the low cement content, which constrained bond development. Overall, small cement additions had minimal influence on shear strength, implying that meaningful improvement may require either higher cement content or supplementary stabilizing additives (Figure 7).

These minor improvements are primarily attributed to limited cementitious bonding between coarse sand grains and enhanced interlocking, which is consistent with the coarse-grained nature and low fines content of the sand. The results align with findings from prior studies, where low cement dosages in sandy soils led to modest frictional

enhancements but minimal cohesion development (e.g., Elyaslankaran et al., 2021; Owino et al., 2022). This suggests that for coarse sands, low cement contents mainly contribute to frictional resistance rather than cohesive strength. The limited effect also implies that achieving substantial shear strength improvement in such sands may require either higher cement dosages or the incorporation of supplementary stabilizers, such as pozzolanic materials (RHA) or fiber reinforcement, which can enhance interparticle bonding and energy absorption (Vafaei et al., 2022; Xiao et al., 2022).

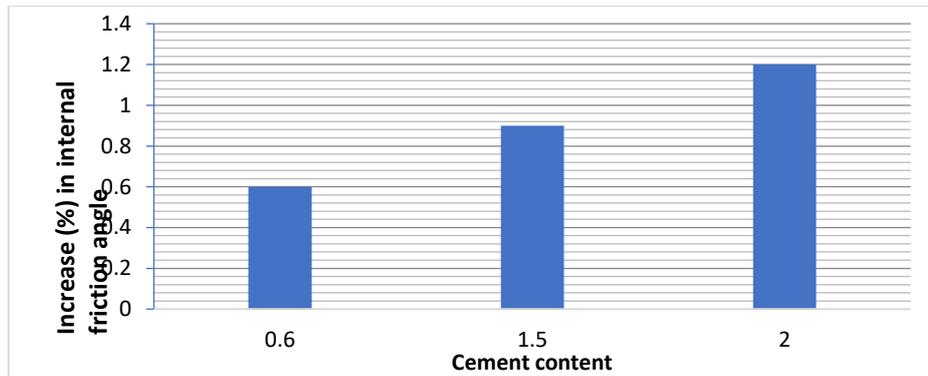


Figure 5: Percentage increase in internal friction angle with different cement contents

### 4.3. Investigation of the Combined Effect of Cement and Rice Husk Ash on the Shear Behavior of Coastal Sand

Direct shear tests were performed on Babolsar coastal sand containing 1% cement with 3%, 5%, and 7% rice husk ash (RHA) to evaluate the effect of RHA on the internal friction angle and cohesion. The samples were prepared by mixing cement and RHA, adding optimum moisture, and curing under standard conditions. Each test was conducted in triplicate at three vertical stress levels. The results (Figure 8) indicated that adding 3% RHA to 1% cement increased the internal friction angle to  $32.56^\circ$  and cohesion to 0.02 kPa. This improvement compared to the sample with 1% cement alone (zero cohesion) demonstrates the formation of cementitious bonds through the pozzolanic reactions of RHA, enhancing soil cohesion.

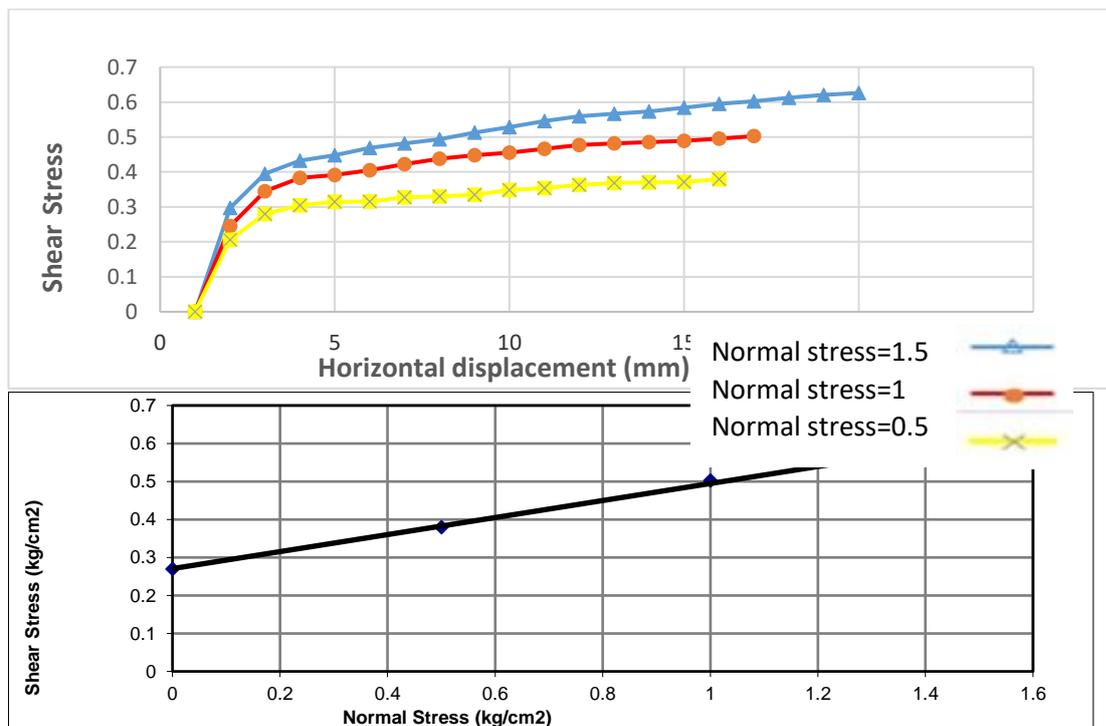


Figure 6: Direct shear test results of sand mixed with 1% cement and 3% rice husk ash

Increasing the RHA content to 5% further enhanced the shear strength of the sand, with the internal friction angle increasing to  $33.04^\circ$  and cohesion to 0.03 kPa. The improvement in friction angle can be attributed to fine RHA particles filling voids between sand grains, promoting better particle-to-particle contact and increasing intergranular friction. The rise in cohesion reflects the formation of additional cementitious bonds and a denser soil structure. The highest shear resistance was recorded in the mix containing 1% cement and 7% RHA, which exhibited an internal friction angle of  $33.60^\circ$  and cohesion of 0.05 kPa. This notable improvement is linked to enhanced pozzolanic reactions and the development of extensive cementitious bonds, while the fine RHA particles further reduced particle mobility by filling interstitial spaces. Overall, the results demonstrate that increasing RHA content progressively raises the internal friction angle, confirming RHA's role as a key pozzolanic material for strengthening sandy soils, particularly when combined with low cement dosages. This combination improves mechanical properties while reducing cement consumption, offering economic and environmental advantages. Nevertheless, excessive RHA may saturate particle surfaces and hinder reaction efficiency, underscoring the need for further studies to establish the optimal RHA content.

Direct shear tests were also performed on Babolsar coastal sand containing 1.5% cement with 3%, 5%, and 7% RHA to evaluate shear strength. Samples prepared with optimum moisture and curing were tested under three vertical stress levels. The results showed that the sample with 1.5% cement and 3% RHA had an internal friction angle of  $32.65^\circ$  and cohesion of 0.06 kPa; with 5% RHA, the angle was  $32.69^\circ$  and cohesion 0.05 kPa; and with 7% RHA, the angle was  $32.38^\circ$  and cohesion 0.07 kPa. While RHA increased cohesion compared to the control (zero cohesion), changes in the internal friction angle were limited, reflecting maintained frictional properties and improved soil cohesion due to pozzolanic reactions.

For samples with 2% cement and 3%, 5%, and 7% RHA, the direct shear results indicated internal friction angles of  $31.56^\circ$ ,  $31.88^\circ$ , and  $31.88^\circ$ , and cohesion values of 0.08, 0.08, and 0.09 kPa, respectively. The increase in cohesion with RHA and cement indicates enhanced internal bonding, while minimal changes in the friction angle ( $31.56\text{--}31.88^\circ$ ) suggest strengthened soil cohesion without significantly altering particle friction.

#### 4.4. Combined Effect of Cement, Carbon Fiber, and Rice Husk Ash on Shear Behavior

Direct shear tests on Babolsar coastal sand with 1% cement, 0.1% carbon fiber (CF), and 3%, 5%, and 7% RHA showed that with 3% RHA, the internal friction angle was  $31.68^\circ$  and cohesion 0.1 kPa; with 5% RHA,  $31.7^\circ$  and 0.1 kPa; and with 7% RHA,  $31.43^\circ$  and 0.11 kPa. RHA increased cohesion, but the internal friction angle changed minimally, indicating improved soil cohesion with limited influence from carbon fibers at this concentration.

With 1.5% cement, 0.1% CF, and 3%, 5%, and 7% RHA, the internal friction angles were  $31.17^\circ$ ,  $30.86^\circ$ , and  $31.41^\circ$  with cohesion values of 0.12, 0.12, and 0.13 kPa, respectively. Cohesion increased, while friction angles remained nearly constant. For 2% cement, 0.1% CF, and 3%, 5%, and 7% RHA, friction angles were  $31.65^\circ$ ,  $31.48^\circ$ , and  $31.44^\circ$ , and cohesion 0.15, 0.15, and 0.17 kPa, respectively, showing similar trends.

For samples with 1% cement, 0.15% CF, and 3%, 5%, and 7% RHA, internal friction angles were  $30.96^\circ$ ,  $30.75^\circ$ , and  $30.49^\circ$  with cohesion 0.16, 0.17, and 0.18 kPa. With 1.5% cement, 0.15% CF, and 3%, 5%, and 7% RHA, friction angles were  $31.23^\circ$ ,  $30.97^\circ$ , and  $31.48^\circ$  with cohesion 0.13, 0.14, and 0.14 kPa after 7 days of curing. With 2% cement, 0.15% CF, and 3%, 5%, and 7% RHA, friction angles were  $30.16^\circ$ ,  $30.13^\circ$ , and  $29.8^\circ$  and cohesion 0.18, 0.19, and 0.21 kPa, respectively.

These results indicate that combining cement, carbon fiber, and RHA significantly increases cohesion, while internal friction angle changes are limited due to increased fines and reduced interparticle friction. This combination effectively improves shear strength, bearing capacity, and the stability of loose sandy soils.

The progressive increase in cohesion with RHA and carbon fiber addition highlights the complementary mechanisms of soil stabilization. RHA contributes through pozzolanic reactions, forming additional cementitious bonds, while carbon fibers provide tensile bridging and restrict particle displacement, particularly in loose sand. The limited changes in internal friction angle suggest that while interparticle friction remains governed by the sand's granular nature, the enhanced cohesion dominates overall shear resistance. These observations align with the findings of Vafaei et al. (2022) and Owino et al. (2022), where natural or basalt fibers improved soil cohesion with minimal effect on friction angle, and with Elyaslankaran et al. (2021), confirming that combining low cement content with pozzolanic additives and fibers can effectively strengthen sandy soils while maintaining cost and material efficiency.

### 4.5. Effect of Curing Time

Direct shear tests were conducted on Babolsar coastal sand containing 2% cement, 7% rice husk ash (RHA), and 0.15% carbon fiber at curing times of 0, 7, 14, and 28 days. The results (Figures 9 and 10) indicated that the internal friction angle increased by 3.45%, 8.48%, and 13.25% after 7, 14, and 28 days, respectively, compared to the one-day sample. This improvement reflects enhanced particle-to-particle contact and the development of cementitious bonds over time. Cohesion showed no significant change at 7 days but increased by 4.76% and 9.52% at 14 and 28 days, respectively, due to the formation and growth of cementitious compounds from pozzolanic reactions and hydration. These results highlight the significant role of curing time in improving the shear strength parameters of stabilized sand. The observed increases in internal friction angle and cohesion with curing time are consistent with the progressive development of cementitious bonds and pozzolanic reactions of RHA, as reported in similar studies (e.g., Eliaslankaran et al., 2021; Vafaei et al., 2022). The 13.25% increase in friction angle and 9.52% increase in cohesion after 28 days indicate that prolonged curing enhances particle interlocking and internal bonding, confirming that both time-dependent hydration and pozzolanic activity are key mechanisms driving the improvement in shear strength. This trend also aligns with the performance gains seen when low cement dosages are combined with RHA and carbon fibers, demonstrating the synergistic effect of additives and curing on mechanical behavior.

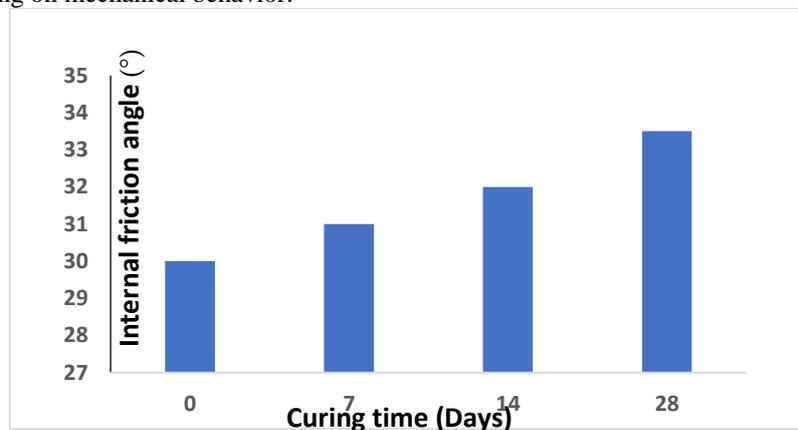


Figure 7: Comparison of the internal friction angle of Babolsar coastal sand containing 2% cement, 7% rice husk ash (RHA), and 0.15% carbon fiber at different curing times.

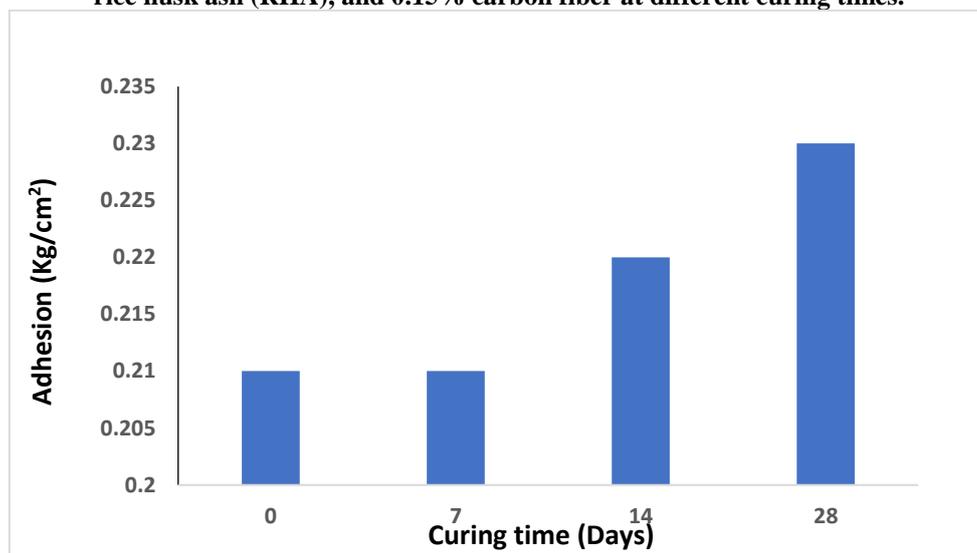


Figure 8: Comparison of cohesion for Babolsar coastal sand containing 2% cement, 7% rice husk ash (RHA), and 0.15% carbon fiber at different curing times.

### 4.6. X-ray Diffraction (XRD) Test

X-ray diffraction (XRD) analysis was conducted on the stabilized Babolsar coastal sand containing 2% cement, 7% rice husk ash (RHA), and 0.15% carbon fiber to investigate mineralogical changes and identify the products associated with the stabilization process (Fig. 9). The diffraction pattern is dominated by a strong peak at  $2\theta \approx$

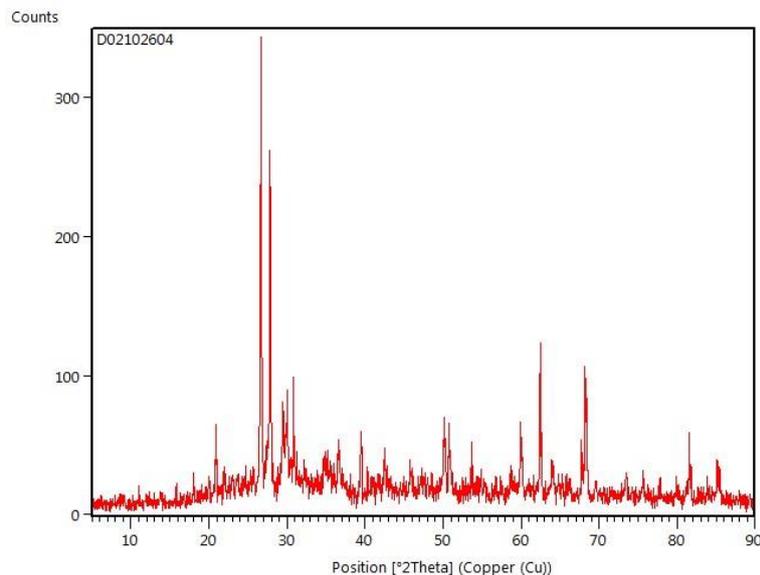
26.6°, corresponding to quartz ( $\text{SiO}_2$ ), which originates from the naturally silica-rich coastal sand. The persistence of this peak after stabilization indicates that the primary crystalline framework of the sand remains unchanged, and the stabilization process does not alter the inherent mineralogy of the base soil.

Additional low-intensity peaks observed around  $2\theta \approx 29\text{--}30^\circ$  are attributed to calcite ( $\text{CaCO}_3$ ), which forms as a result of cement hydration followed by partial carbonation during curing. The presence of calcite confirms the occurrence of cement-related chemical reactions and contributes to pore filling and interparticle bonding within the soil matrix. Diffraction features in the range of  $40\text{--}60^\circ$  are associated with calcium-containing hydration products; however, these phases exhibit low crystallinity and therefore appear as weak or diffuse signals rather than sharp peaks.

Rice husk ash does not exhibit distinct crystalline peaks in the diffractogram, which is consistent with its predominantly amorphous silica structure. Instead, a slight increase in background intensity in the  $20\text{--}30^\circ$  range suggests the presence of amorphous or poorly crystalline reaction products. This behavior is indicative of pozzolanic reactions between the amorphous silica in RHA and calcium hydroxide released during cement hydration, leading to the formation of secondary cementitious compounds such as calcium silicate hydrate (C–S–H). These products are known to be poorly crystalline and are therefore not easily detected as discrete peaks in XRD analysis.

Carbon fibers are not identifiable in the XRD pattern due to their non-crystalline nature and low dosage; consequently, their contribution to soil improvement is primarily mechanical rather than mineralogical. The combined action of cement hydration, pozzolanic reactions of RHA, and mechanical reinforcement by carbon fibers results in a denser soil matrix with enhanced interparticle bonding. This composite stabilization mechanism explains the observed increase in cohesion and shear resistance obtained from direct shear testing, while the internal friction angle remains largely controlled by the granular nature of the sand.

Overall, the XRD results support the mechanical test findings by demonstrating that strength enhancement arises mainly from the formation of amorphous cementitious bonds and microstructural densification rather than from significant changes in the crystalline mineral composition of the soil.



**Figure 9: XRD test results.**

#### 4.7. Scanning Electron Microscopy (SEM) Test

Scanning electron microscopy (SEM) was conducted on the optimal stabilized mixture containing 2% cement, 7% rice husk ash (RHA), and 0.15% carbon fiber to investigate the microstructural features governing the observed mechanical behavior (Figure 10). The micrographs reveal a dense and well-integrated matrix in which sand particles are effectively bonded by hydration and pozzolanic reaction products. The intergranular voids are

largely filled with gel-like phases exhibiting morphologies consistent with calcium silicate hydrate (C-S-H), indicating the development of a continuous cementitious network that enhances particle interlocking and load transfer.

Fine RHA particles are observed to be embedded within the cementitious matrix, appearing as angular and irregular morphologies rather than distinct crystalline phases. This observation is consistent with the predominantly amorphous nature of RHA and suggests its active participation in pozzolanic reactions with calcium hydroxide released during cement hydration. The formation of secondary cementitious products contributes to matrix densification and a reduction in pore connectivity, which directly supports the measured increase in soil cohesion.

Carbon fibers are clearly identifiable as elongated, well-dispersed filaments within the matrix. In several regions, strong fiber-matrix adhesion is evident, indicating effective stress transfer across the fiber-soil interface. The fibers act as micro-reinforcement elements, bridging interparticle gaps and restraining localized deformation, thereby enhancing resistance to shear-induced particle rearrangement. This bridging mechanism contributes to the observed improvement in internal friction angle by promoting mechanical interlocking and limiting dilative behavior under shear loading.

Overall, the combined action of cement hydration, RHA-induced pozzolanic reactions, and fiber reinforcement results in a compact and mechanically integrated microstructure. This synergistic microstructural evolution provides a clear mechanistic explanation for the enhanced shear strength parameters observed in the mechanical tests.

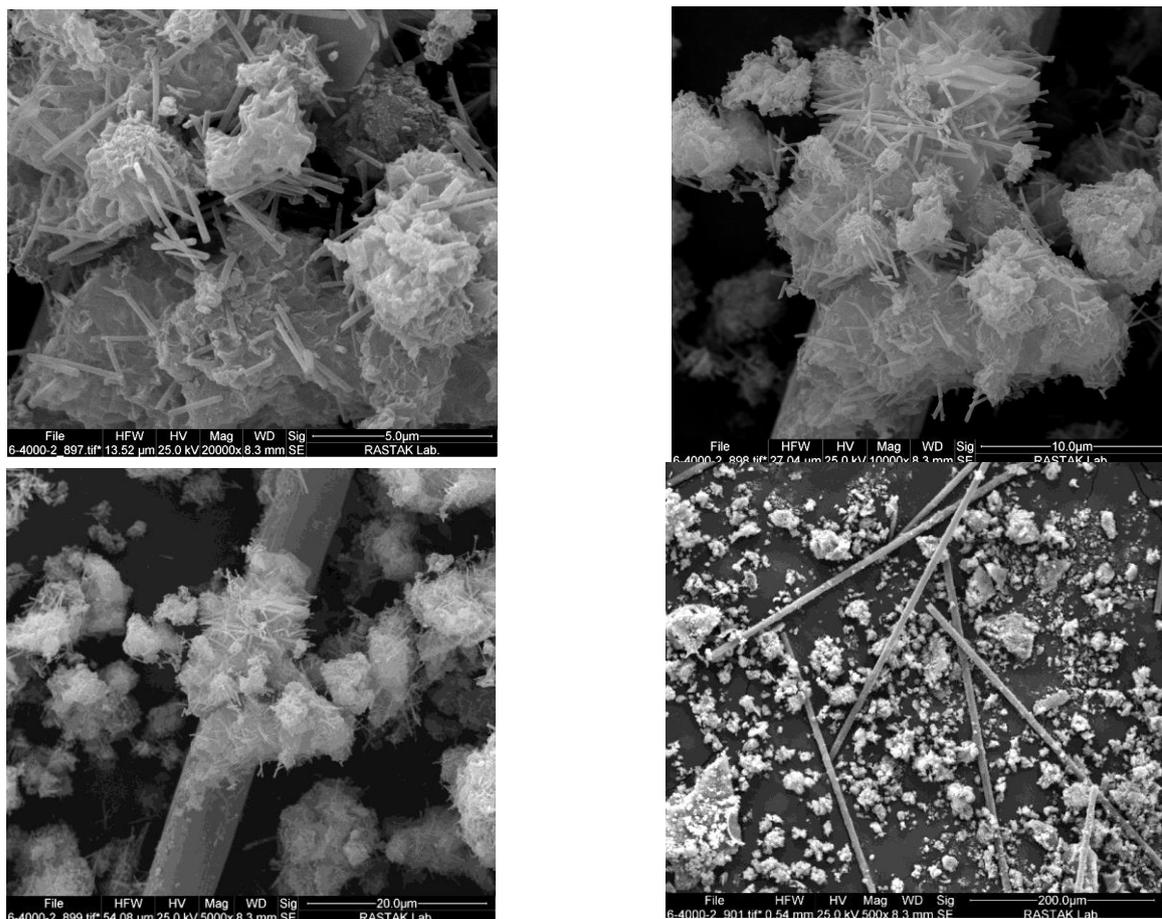


Figure 10: SEM test results.

## CONCLUSION

This study examined the shear behavior of Babolsar coastal sand stabilized with small dosages of cement, rice husk ash (RHA), and carbon fibers (CF) at different curing periods. The untreated sand exhibited a purely frictional response, characterized by an internal friction angle of  $31.91^\circ$  and zero cohesion, consistent with the granular and cohesionless nature of clean sands. The inclusion of cement at contents up to 2% resulted in only marginal increases in the internal friction angle and negligible changes in cohesion, indicating that low cement dosages alone are insufficient to induce significant strength enhancement.

In contrast, the combined use of cement and RHA led to a noticeable increase in cohesion, attributed to improved particle interlocking, void filling by fine RHA particles, and the formation of cementitious bonds through pozzolanic reactions, while the internal friction angle remained largely unchanged. The addition of carbon fibers to the cement–RHA system further enhanced cohesion, as the fibers contributed to microcrack control and improved stress transfer between particles, without significantly affecting the frictional component of shear strength.

Curing time played a critical role in strength development. Both cohesion and internal friction angle increased with prolonged curing, with the most pronounced improvements observed after 28 days, reflecting the continued progression of cement hydration and pozzolanic reactions. Overall, the results indicate that stabilization using a cement–RHA–CF system promotes the formation of a denser and more cohesive soil matrix while preserving the inherent frictional behavior of sandy soils. From a practical perspective, a minimum curing period of 28 days is required to achieve the full mechanical benefits of this stabilization approach for coastal geotechnical applications.

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