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Mechanical Behavior of Polypropylene-Fiber-Reinforced Chlef Soil: An Experimental Study

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Abstract:
This study examines the effect of polypropylene fiber reinforcement on the mechanical behavior of clean sand and silty sand mixtures under shear and one-dimensional compression. Direct shear tests were performed at 50% relative density under normal stresses of 100, 200, and 400 kPa, with fiber contents of 0%, 0.3%, 0.6%, and 0.9%. Fiber inclusion changed the soil response from strain-softening to more ductile behavior, increasing both peak and residual shear strength and delaying peak occurrence. The most significant gains were observed at 0.9% fiber content, especially under higher confining pressures, due to improved fiber mobilization and soil–fiber interaction. Shear strength envelopes showed increasing internal friction angles and apparent cohesion with higher fiber content. For clean sand, cohesion increased from 11.5 kPa (unreinforced) to 25 kPa at 0.9% fiber content. Silty sands showed a similar trend, with 10% silt improving fiber anchorage, reducing void ratio, and enhancing stress transfer. Oedometer test results confirmed a void ratio decrease with fiber inclusion, particularly in silty sands. The compressibility coefficient (Cc) increased with fiber content, indicating higher deformability and energy absorption. Conversely, the secant oedometer modulus (Esecant) decreased as fiber content rose: from 28.09 MPa to 20 MPa for clean sand, and to 8 MPa for the sand–silt mixture. This stiffness reduction is attributed to the flexibility of the fiber network, leading to a more ductile and controlled compressive response.

***Keywords*: Polypropylene, fibers, Sand, Silt, Reinforcement**

List of symbols

G_s	Specific gravity of sand
D_{10}	Effective diameter
D_{50}	Average diameter
C_c	Compressibility coefficient
f_c	Fines content
$_{Fc}$	Fiber content
φ	Internal friction angle
c	cohesion
e_{max}	Maximum void ratio
e_{min}	Minimum void ratio
Dr	Relative density

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σ_n	Normal stress
τ_{max}	Maximum shear strength
τ	Shear strength
ΔH	Horizontal displacement
R^2	Coefficient of détermination
W	Water content
E_{secant}	Secant oedometer modulus

1.INTRODUCTION:

The mechanical stability of soils can be enhanced using stabilizers such as cement, lime, or fly ash (Consoli et al., 2009, Belhassena et al.2021, Bellabaci et al.2021), commonly applied in embankments, slope stabilization, and foundations (Terzaghi et al., 1996). However, due to their environmental impact—especially CO_2 emissions—more sustainable solutions are being investigated. One promising approach is the use of randomly distributed fibers, particularly polypropylene (PP) fibers, which improve shear strength, ductility, and deformation resistance (Gray and Ohashi, 1983).
Several studies have confirmed the benefits of fiber reinforcement in sandy soils. [Maher and Gray (1990) and Yetimoglu and Salbas (2003] reported that the addition of synthetic fibers increases both apparent cohesion and internal friction angle. Vafaei et al. (2022) Showed that hemp fibers significantly enhance the shear strength and deformation resistance of sand. Pydi et al. (2025) Investigated the stabilization of coastal fine sand using polypropylene fibers as a cost-effective alternative to cement. Their results showed that incorporating 12 mm fibers at 1% content significantly improved strength, ductility, and CBR value, making the sand more suitable for construction. Other studies [Arora and Audilek (2005), Consoli et al. (2009) and Gao and Zhao (2013)] have shown that fibers enhance both cohesion and internal friction angle in stabilized soils. Under dynamic loading, fibers help prevent static liquefaction by modifying soil behavior under monotonic and cyclic loading. [Dos santos et al. (2010) and Santoni et al. (2001)] The efficiency of fiber reinforcement depends on factors such as aspect ratio, orientation, distribution, and content [Consoli et al. (2011) and Maher and Gray (1990)].
The benefits of fiber reinforcement extend beyond shear strength. Soil compressibility critical for settlement and bearing capacity can also be reduced. Meddah et al. (2023) Demonstrated that adding PP fibers to highly plastic Algerian clay decreased compressibility and increased unconfined compressive strength. Anagnostopoulos et al. (2014) Highlighted how fiber distribution and content affect stress transmission by forming internal “bridges” that limit particle displacement. Kutanaei et al. (2025) Conducted consolidated drained triaxial tests to study how polyvinyl alcohol (PVA) fibers and cement affect the volumetric behavior of sand. They examined the combined influence of fiber content, cement ratio, confining pressure, and relative density. Their findings show that while higher relative density and cement content increase dilatation, adding fibers and increasing confining pressure reduce it, providing valuable insights into the complex interaction of these factors in reinforced cemented sand. Jiang et al. (2025] Investigated the effect of coir fiber on the compressibility of calcarenite sand treated with Enzyme-Induced Calcium Carbonate Precipitation (EICP). Their findings show that coir fiber alters the void ratio behavior during compression, with low fiber content slightly reducing compaction and higher content enhancing it. The study demonstrates that natural fibers can effectively reinforce weak sands, improving their mechanical properties and offering a sustainable solution for geotechnical applications
This study aims to evaluate the influence of polypropylene fibers on the shear strength and compressibility characteristics of sandy soils. Direct shear and oedometer tests were conducted on both clean sand and a sand–silt mixture (containing 10% silt), with varying fiber contents (0%, 0.3%, 0.6%, and 0.9%). The findings provide new insights into the mechanical behavior of fiber-reinforced sandy soils and demonstrate the potential of polypropylene fibers to improve soil performance in a sustainable way.

2. MATERIALS AND APPARATUS USED:

2.1. Materials:

The materials used in this study are clean Chlef sand and a sand-silt mixture containing 10% silt by weight. The polypropylene fibers were added to both materials at varying contents of 0.3%, 0.6%, and 0.9% by dry weight of soil. Chlef sand is well-known natural sand frequently studied in geotechnical research [Bouri et al. (2019), Bouri et al. (2021), Bouri et al. (2023), Brahim et al. (2016), Brahim et al. (2018) and Brahim et al. (2023), Nougar et al.2021, Nougar et al.2022, Nougar et al.2024]. The silt used in the mixture was obtained from the

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same sand source, extracted by wet sieving through a 0.08 mm sieve. The physical properties of the clean sand and the sand-silt mixture, such as specific gravity (Gs), minimum and maximum void ratios (e_{min}, e_{max}), and grain size distribution parameters (D_{10}, D_{50}, Cu), were determined in accordance with ASTM D 4254–00 [2002] and ASTM D 4253–00 [2002]. These properties are summarized in Table 1. The grain size distribution curves of both materials are shown in Fig. 1.

Table 1 Physical parameters of sand-silt mixtures

Materials	f_c (%)	G_s	D_{10} (mm)	D_{50} (mm)	C_u	e_{min}	e_{max}
Clean sand	0	2.650	0.17	0.41	2.82	0.623	0.848
Sand silt mixtures	10	2.653	0.08	0.38	5.28	0.487	0.811

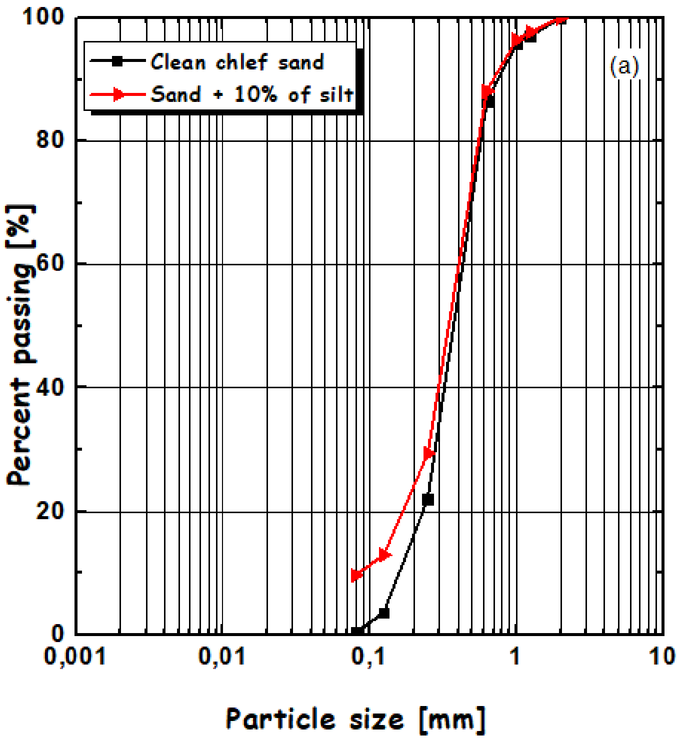

Fig. 1: Particle size distribution curves

2.2. Direct shear test:

A total of 24 direct shear tests were carried out using a square shear box device (60 × 60 mm²), in accordance with ASTM D 3080 [2005]. The tests were conducted on two types of materials: clean sand and sand mixed with 10% silt (by dry weight), each reinforced with three polypropylene fiber contents: 0.3%, 0.6%, and 0.9%. All samples were prepared at a relative density of 50%, corresponding to a medium-dense state. The specimens were prepared in four layers, each layer being manually compacted using a tamping device to achieve the target void ratio. The initial sample height was maintained at 20 mm. The tests were performed under three normal stresses: 100, 200, and 400 kPa, to evaluate the influence of fiber reinforcement on the shear strength under different confining conditions. All tests were carried out in dry conditions (initial water content w = 0%), without any moisture added to the mixtures.

2.3. Oedometer test:

Oedometer tests were performed on clean sand and a sand + 10% silt mixture, each reinforced with polypropylene fibers at contents of 0.3%, 0.6%, and 0.9% (by dry weight). The samples were prepared and placed in oedometer rings of 70 mm diameter and 20 mm height, following the procedure described in ASTM D 2435 [1997]. During sample preparation, the fibers were progressively added to the dry sand or sand–silt mixture in small portions, with continuous manual mixing to ensure visual homogenization. After complete addition, the materials were mixed thoroughly for 10 minutes. All samples were prepared under dry conditions (initial water content w = 0%), using a relative density of 50%. The specimens were built in four equal layers, each placed by free fall from a small height (about 5 mm), then lightly compacted using a hand tamper to achieve the target void ratio. The prepared material was placed directly into the oedometer ring and dynamically compacted until the desired density was reached. After installation of the top cap, samples were saturated by flooding, and a 24-hour saturation period was allowed before the application of the vertical loading. The loading was applied incrementally, starting with 25 kPa, and doubled every 24 hours up to a maximum load of 800 kPa. Settlement readings were recorded at each stage to assess the compressibility of the fiber-reinforced samples.

3. RESULTS AND DISCUSSION

3.1. Direct shear test

The shear stress–horizontal displacement curves presented in Fig.2 (a–c) illustrate the mechanical behavior of clean sand reinforced with various polypropylene fiber contents (Fc = 0%, 0.3%, 0.6%, and 0.9%) under normal stresses of 100, 200, and 400 kPa, respectively, at a relative density of 50%. These curves are critical in understanding the influence of fiber inclusion on the shear response of granular soils.

In general, the unreinforced sand exhibits a typical strain-softening behavior, characterized by a distinct peak followed by a gradual decrease in shear stress with increasing horizontal displacement. However, the introduction of fibers alters this behavior significantly. All reinforced specimens demonstrate a more ductile response, with higher post-peak residual strengths and delayed peak occurrences, indicating enhanced resistance to deformation.

As seen in Fig.2 (a), under a normal stress of 100 kPa, the addition of 0.3% and 0.6% fibers improves the peak shear strength compared to the unreinforced sand. However, the most notable improvement is observed at 0.9% fiber content, where the curve shows a pronounced increase in both peak and residual shear strength. A similar trend is observed at higher normal stresses (Fig.2 (b–c)). Under 200 and 400 kPa, fiber-reinforced samples consistently outperform the unreinforced specimen, with the 0.9% fiber mixture demonstrating the highest peak strength and a more stable post-peak response.

The enhancement in shear strength is attributed to the mechanical interlocking and tensile resistance provided by the randomly distributed fibers. At lower strains, the contribution of fibers remains limited due to initial slippage and orientation adjustments. However, at higher strains, the fibers become mobilized, stretch, and bridge soil particles, leading to improved load transfer and confinement within the sand matrix.

Moreover, the effect of confining pressure is evident across all fiber contents. As normal stress increases from 100 to 400 kPa, the magnitude of shear strength increases for all mixtures. Notably, the beneficial effect of fiber reinforcement is more pronounced at higher normal stresses, which is consistent with the findings of previous studies Consoli et al. (2009), Dos Santos et al. (2010) and Heineck et al. (2009). This suggests that fiber-soil interaction mechanisms become increasingly effective under higher confining conditions.

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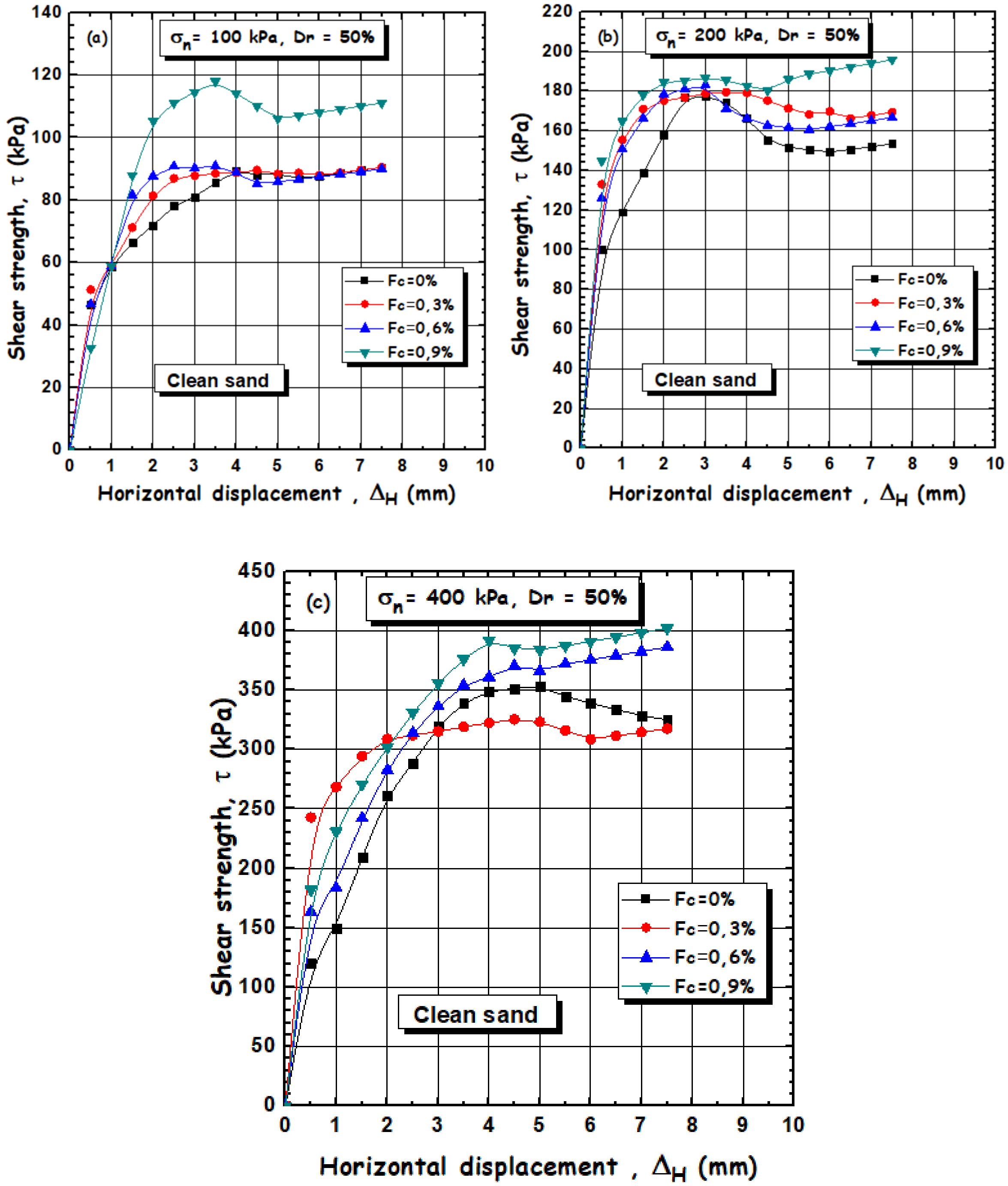

Fig. 2: Variation of shear strength as a function of horizontal displacement for clean sand, a) σ_n = 100 kPa, b) σ_n = 200 kPa, c) σ_n = 400 kPa

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The figure 3 presents the intrinsic relationship between shear stress (τ) and normal stress (σ_n) for clean sand (Dr = 50%) reinforced with varying polypropylene fiber contents (Fc = 0%, 0.3%, 0.6%, and 0.9%). Each dataset is fitted with a linear regression equation of the form $\tau = a(\sigma_n) + b$, with a high correlation coefficient ($R^2 = 0.99$), indicating excellent agreement with the experimental data. This intrinsic curve clearly demonstrates a progressive improvement in shear strength as fiber content increases. The slope of each line, corresponding to the internal friction angle (φ), while the y intercept, representing apparent cohesion (c), the trend shows a progressive increase in both the slope and intercept with increasing fiber content. For Fc = 0%, the slope is 0.89, indicating frictional behavior with minimal cohesion. With fiber addition, the slope increases (up to 0.99 at Fc = 0.9%) and the intercept rises from 12.47 kPa to 15.5 kPa, reflecting enhanced apparent cohesion and interparticle friction due to the presence of fibers and fines. These results confirm that polypropylene fiber inclusion not only improves peak shear strength but also contributes to increased ductility and overall mechanical performance of silty sands. The most notable improvement occurs at Fc = 0.9%, confirming the synergistic interaction between fiber content and fines, and reinforcing the potential of this technique for ground improvement applications in fine-containing sandy soils .These results are in good agreement with [30, 28 and 13]

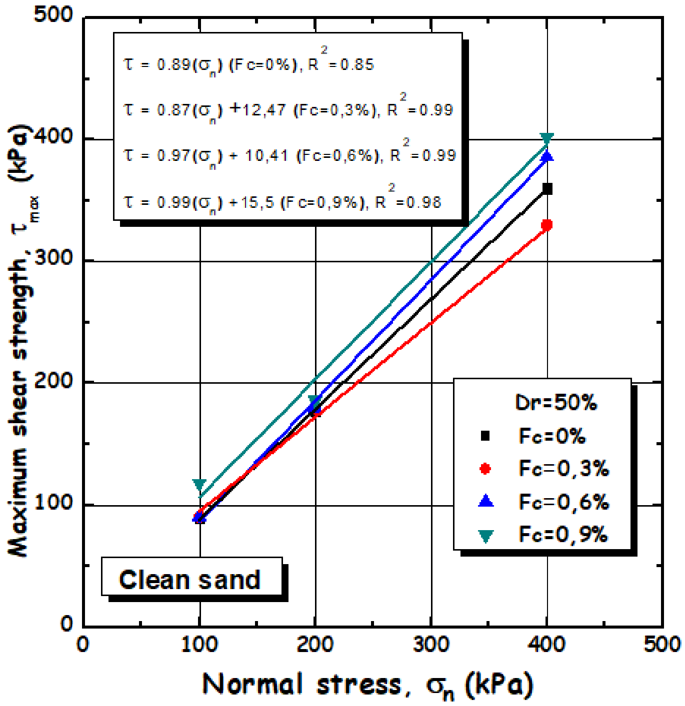

Fig. 3: Variation of peak shear stress as a function of normal stress for clean sand with different fiber contents

The shear stress–horizontal displacement curves presented in Fig. 4 (a–c) illustrate the mechanical behavior of sand mixed with 10% silt and reinforced with various polypropylene fiber contents (Fc = 0%, 0.3%, 0.6%, and 0.9%) under normal stresses of 100, 200, and 400 kPa, respectively, at a relative density of 50%. These curves are essential for understanding the influence of fiber inclusion in silty sand matrices and how the presence of fines alters the shear response of fiber-reinforced soils.

In general, the unreinforced silty sand (Fc = 0%) exhibits a strain-softening behavior similar to that of clean sand, with a peak followed by a noticeable reduction in shear stress as horizontal displacement increases. The addition of fibers modifies this behavior, leading to a more ductile response with delayed peaks and higher residual strengths. At 100 kPa (Fig. 4a), fiber reinforcement improves peak shear strength moderately for Fc = 0.3% and 0.6%, while the most significant increase is observed at Fc = 0.9%, which also provides a stable post-peak response. At higher normal stresses (200 and 400 kPa in Figs. 4b and 4c), the improvement is even more pronounced. The 0.6% and 0.9% fiber-reinforced specimens demonstrate substantial gains in both peak and residual strength, indicating that fiber mobilization becomes more effective under higher confining pressures.

The observed enhancements are attributed to the combined effects of fiber-soil interaction and the presence of silt, which reduces void ratios and enhances fiber anchorage within the soil matrix. Initially, fiber contribution is

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limited due to slippage and reorientation; however, as deformation progresses, fibers become increasingly mobilized, bridging particles and confining the structure, especially in the presence of fine particles that improve contact efficiency.

Moreover, the effect of confining pressure remains consistent across all fiber contents: as σ_n increases from 100 to 400 kPa, the shear strength increases markedly, particularly for higher fiber contents. The reinforcing effect is amplified in the silty sand due to better fiber entanglement and reduced interparticle spacing. This aligns with the findings of prior studies [e.g.19 and 16], showing that fine content can enhance the mechanical contribution of fibers in granular soils.

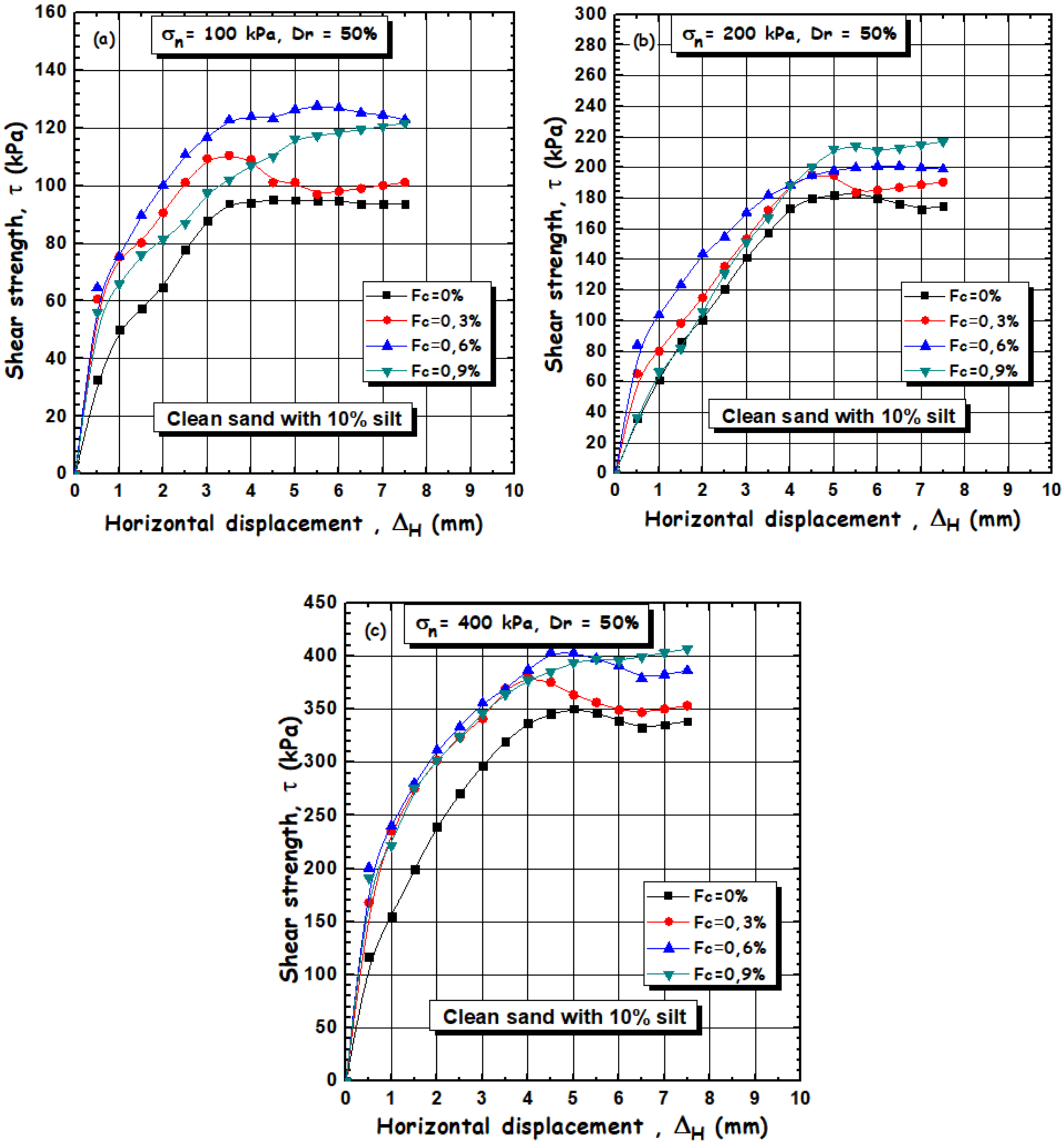

Fig. 4: Variation of shear strength as a function of horizontal displacement for clean sand with 10% silt, a) σ_n = 100 kPa, b) σ_n = 200 kPa, c) σ_n = 400 kPa

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Figure 5 presents the intrinsic shear strength envelope for the silty sand mixtures, fitted with linear regression models of the form $\tau = a(\sigma_n) + b$. The trend shows a progressive increase in both the slope and intercept with increasing fiber content. For Fc = 0%, the slope is 0.89, indicating frictional behavior with minimal cohesion. With fiber addition a significant rise from 11.5 kPa for unreinforced sand to 25 kPa for sand reinforced with 0.9% fibers. These results confirm that fiber inclusion enhances not only peak shear strength but also the induced cohesion of the sand-fiber mixture, which is consistent with the previously discussed shear stress–displacement behavior. The most notable improvement occurs at Fc = 0.9%, where the slope (0.96) and cohesion (25 kPa) are highest, highlighting the synergistic effect of higher fiber content. The most notable improvement occurs at Fc = 0.9%, confirming the synergistic interaction between fiber content and fines, and reinforcing the potential of this technique for ground improvement applications in fine-containing sandy soils. These results are in good agreement with [Brahimi et al. (2023), Pydi et al. (2025) and Shao et al. (2014)]

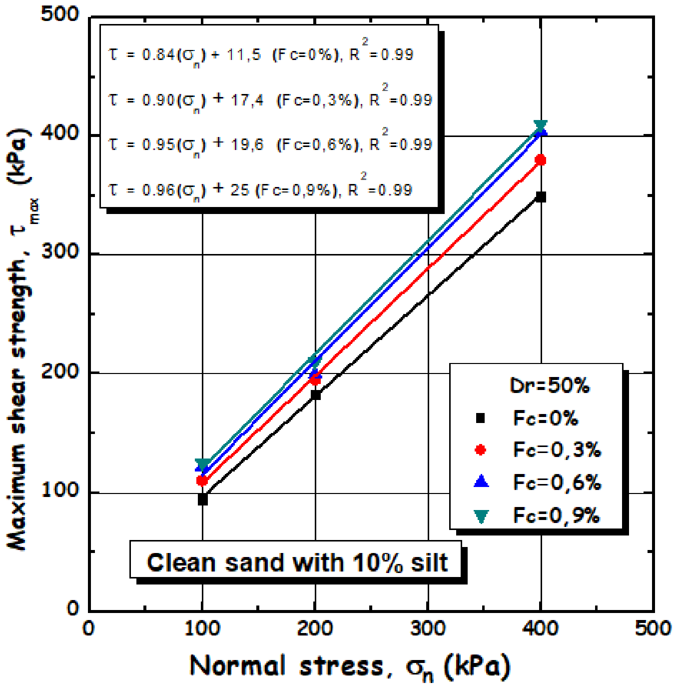

Fig. 5: Variation of peak shear stress as a function of normal stress for clean sand with 10% silt and for different fiber contents

3.2. Oedometer test results

Figures 6a and 6b depict the evolution of the void ratio (*e*) as a function of oedometer pressure (σ') for clean Chlef sand (Figure 6a) and a sand–silt mixture containing 10% silt (Figure 6b), each reinforced with varying contents of polypropylene fibers (0%, 0.3%, 0.6%, and 0.9%).

In both cases, the void ratio decreases progressively with increasing vertical stress, which reflects the typical compressive response of granular soils under one-dimensional loading. However, the introduction of fibers noticeably alters this trend by modifying the packing structure and particle interaction.

For clean sand (Figure 6a), fiber inclusion slightly reduces the void ratio at all stress levels, with the most evident effect observed at 0.9% fiber content. This reduction suggests that fibers contribute to maintaining a denser structure by limiting particle rearrangement, particularly at higher stresses. The interlocking and bridging effects induced by the fibers help stabilize the granular skeleton and reduce void space during compression.

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In the sand + 10% silt mixture (Figure 6b), the influence of fibers is more pronounced. The void ratio decreases more significantly with fiber addition, especially beyond 100 kPa. The sample reinforced with 0.9% fibers shows the lowest void ratio across the entire stress range, indicating enhanced densification. The presence of fines likely improves fiber-soil interaction, increasing the cohesion within the matrix and promoting more efficient stress transfer and volume reduction.
Comparing both figures, the fiber effect is more substantial in silty sand than in clean sand. This can be attributed to the better fiber retention and mechanical interlock provided by the fines, which enhance the stabilizing role of the fibers. These observations underscore the ability of polypropylene fibers to effectively reduce the void ratio under loading, particularly in soils with fine content, thus improving structural integrity and reducing settlement potential.

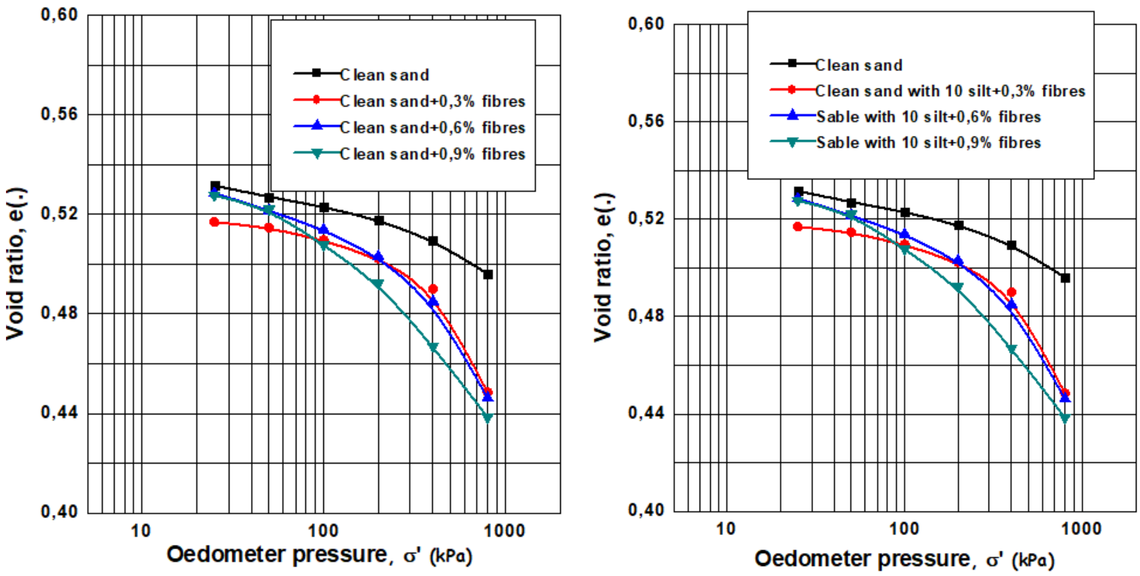

Fig. 6: Variation of void ratio as a function of oedometer pressure, a) Clean sand, b) Clean sand with 10% silt

Figures 7 show the variation of the compressibility parameter Cc versus the fine content Fc, this parameter was determined from the compressibility curves and using the following equation:

$$C_c = \frac{\Delta e}{\Delta \log \sigma'} \quad (1)$$

The results demonstrate a clear increase in the compressibility coefficient (*Cc*) with rising fiber content. For sand mixed with 10% silt, *Cc* values increased from 0.048 to 0.13, whereas for clean sand, the increase was from 0.044 to 0.094. This behavior can be attributed to the ductile nature of fiber-reinforced soils, which promotes higher deformability under loading by increasing the mixture's plasticity and flexibility [Li et al. (2020) and Consoli et al (2011)].
These findings align with previous studies on fiber-reinforced soils, which have shown that increased fiber content often leads to higher compressibility. This is due to the greater energy absorption and redistribution capacity provided by the fibers during compression [Kadhim et al. (2022) Mirzababaei et al. (2017)]. Moreover, investigations on fiber-reinforced clayey soils confirm that fibers contribute to a more progressive and controlled settlement behavior, enhancing performance in geotechnical applications requiring stability and ductility [Babu and Chouksey (2011) and Santoni et al. (2001)]
Overall, the results confirm that polypropylene fiber inclusion significantly affects both the void ratio evolution and compressibility behavior, reinforcing its potential as a practical method for improving soil performance under compressive loads.

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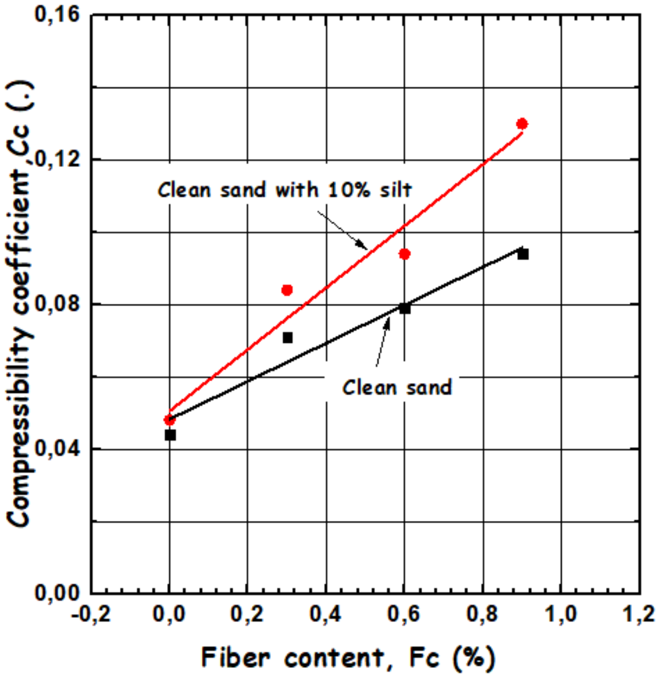

Fig. 7: Variation of compressibility coefficient as a function of fiber content for clean sand and clean sand with 10% silt

Figure 8 illustrate the variation of the secant oedometric modulus (E_{secant}) as a function of fiber content for both clean sand and sand mixed with 10% silt. The secant oedometric E_{secant} module is another classic representation of soil compressibility by the oedometric test. It is defined by (Eq. 2):

$$E_{secant\,(\sigma'va-\sigma'vb)} = \frac{\sigma'_{va} - \sigma'_{vb}}{H_a - H_b} H_i \qquad (2)$$

H_a: height of sample at the end of the consolidation under oedometer stress σ'va
H_b: height of sample at the end of the consolidation under oedometer stress σ'vb
Hi: initial height of sample
The results show a consistent decrease in modulus values with increasing fiber content, confirming that the inclusion of polypropylene fibers reduces the stiffness of the soil under one-dimensional compression. This reduction is due to the increased deformability introduced by the fibers, which disrupt the contact network between soil particles and promote more flexible, ductile behavior during loading. For clean sand, the secant modulus decreases from 28.09 MPa to 20 MPa as fiber content increases to 0.9%, whereas for the sand–silt mixture, it drops more sharply—from 28.09 MPa to 8 MPa. This greater reduction in silty sand is attributed to the presence of fines, which enhance fiber-soil interaction and facilitate more efficient fiber mobilization, thereby increasing the compressibility of the mixture. Although this behavior implies a loss in stiffness, it also reflects improved energy dissipation and ductility, which are desirable in many geotechnical applications such as seismic zones, lightweight embankments, or backfills, where controlled deformation is essential for long-term performance.

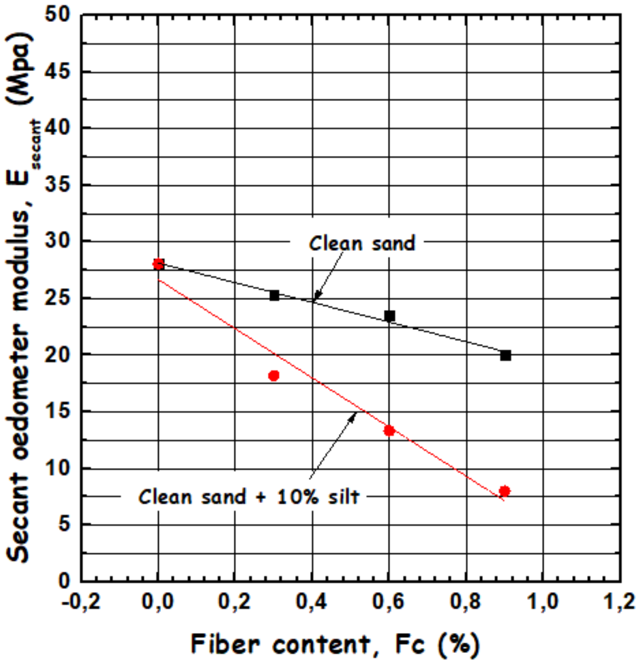

Fig. 8: Variation of secant modulus as a function of fiber content for clean sand and clean sand with 10% silt

4. CONCLUSION:

This study has demonstrated the significant role of polypropylene fiber reinforcement in enhancing the mechanical behavior of both clean and silty sands. Direct shear tests revealed that fiber inclusion transforms the stress–strain response from brittle to ductile, marked by increased peak and residual shear strengths and improved post-peak behavior. The optimal performance was consistently observed at a fiber content of 0.9%, especially under higher confining pressures, where fiber mobilization and soil-fiber interaction are maximized.

The improvement in shear strength was further confirmed through linear shear strength envelopes, which showed a clear increase in both internal friction angle and apparent cohesion with increasing fiber content. The addition of 10% silt amplified the reinforcing effect, due to enhanced fiber anchorage and reduced interparticle spacing, highlighting a synergistic interaction between fibers and fines.

Oedometer test results reinforced these findings by showing a consistent reduction in void ratio with fiber inclusion, particularly in silty sands. The compressibility coefficient (Cc) increased with fiber content, reflecting the ductile and energy-absorbing nature of the reinforced mixtures. These changes suggest that fiber-reinforced soils exhibit improved densification and settlement behavior under vertical loads.

Additionally, the evolution of the secant oedometer modulus E_{secant} as a function of fiber content confirmed a general reduction in stiffness with increasing fiber dosage. For clean sand, the modulus decreased from 28.09 MPa to 20 MPa**,** whereas for the sand–silt mixture, it dropped more sharply from 28.09 MPa to 8 MPa at 0.9% fiber content. This significant decrease reflects the enhanced deformability and flexibility of fiber-reinforced soils, particularly in the presence of fines, where improved fiber anchorage and interparticle contact facilitate greater compressibility.

The inclusion of polypropylene fibers especially at 0.9% significantly improves the strength, ductility, and compressibility characteristics of sandy soils, with enhanced effects observed in the presence of fines. These findings confirm the potential of fiber reinforcement as a sustainable and effective technique for ground improvement in geotechnical applications, particularly where reducing settlement and enhancing shear resistance are critical.

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