Journal of GeoEngineering, Vol. 18, No. 2, pp. 045-058, June 2023
http://dx.doi.org/10.6310/jog.202306_18(2).1

INFLUENCE OF PARTICLE SIZE INDEX ON SHEAR PROPERTIES OF COHESIONLESS SOILS ADMIXTURE WITH FLY ASH BINDER

Amine Taibi [1], Youcef Mahmoudi [2*], Abdellah Cherif Taiba [3], Hamou Azaiez [4], Mostefa Belkhatir [3,5]

ABSTRACT

Shear strength evaluation of granular soils represents one of the most important aspects in the field of geotechnical engineering to analyze the soil behaviors and eventually identifying instability problems in different earth-structures, such as embankments, retaining walls, bearing capacity and deep foundations. In this context, the present study intends to clarify the influence particle size characteristics and fly ash fraction on the shear response of sand-fly ash mixtures. To achieve this goal, a set of direct shear box tests was carried out on three granular classes derived from natural sand having different minimum grain diameters ($D_{\min}$ = 0.08, 0.63, and 2.00 mm). The sandy samples were mixed with different percentages of fly ash ranging from 0% to 15%. The dry funnel pluviated sand-fly ash mixture samples were reconstituted at an initial relative density of 28 ± 3% and subjected to three normal stresses (σ_n = 100, 200, and 300 kPa). The obtained results showed that the minimum grain diameter and the fly ash induced noticeable effects on the shear behavior of the studied assemblies. It was found that the increase of the minimum grain diameter and the increment of the fly ash content induce a remarkable improvement in the shear strength of the tested materials. Moreover, a new parameter was introduced in this investigation known as particle size index in order to highlight the effect of the grain size variation on the behavior of the tested materials. The results indicate that the particle size index correlates very well with the peak friction angle of the sand-fly ash mixtures. In addition, the new suggested parameter appears as a pertinent component in the prediction of the shear properties of the cohesionless soils improved by fly ash which is commonly used in many geotechnical engineering applications.

Key words: Shear strength, direct shear box, minimum grain diameter, sand-fly ash mixtures.

1. INTRODUCTION

The shear properties evaluation of soils is one of the fundamental aspects in the field of geoengineering. The stability of designed civil, hydraulics and underground structures (Wang *et al.* 2013; Cherif Taiba *et al.* 2016, 2021; Azaiez *et al.* 2021a, b) such as: tunnels, retaining walls, shallow and deep foundations, especially, embankments, rely on shear properties. Moreover, the mechanical response of soils is related to several problems and deformation of different types of granular materials according to the impacts of the applied initial loading conditions. Therefore, the evaluation of shear strength of these soils has urged researchers to reinforce or treat to improve their mechanical characteristics for various construction purposes (Meyerhof 1970). Thus, many researchers have focused on studying the impacts of different parameters on the mechanical performance of granular materials on stabilization process of soils (Janalizadeh *et al.* 2013; Belkhatir *et al.* 2014; Mahmoudi *et al.* 2020, 2021). The particle shape characteristics were commonly considered as a determinant parameter among the others influencing the mechanical characterization of granular materials. Borhani *et al.* (2016); Alshibli *et al.* (2018), Cherif Taiba *et al.* (2018, 2022), and Xiao *et al.* (2019) found that the particle shape appeared as a remarkable influencing factor to the stress-strain response of granular soils.

Manuscript received July 29, 2022; revised November 26, 2022; accepted March 28, 2023.
[1] Ph.D. candidate, Laboratory of Structures, Geotechnics and Risks, University of Chlef, Algeria.
[2*] Associate Professor (corresponding author), Laboratory of Material Sciences & Environment, University of Chlef, Algeria (e-mail: mahmoudiyoucef16@yahoo.fr).
[3] Associate Professor, Laboratory of Material Sciences & Environment, University of Chlef (Algeria), Laboratory of Architecture, cities and Environment, University of Chlef, Algeria.
[4] Ph.D., Laboratory of Material Sciences & Environment, University of Chlef, Algeria.
[5] Professor, Alexander von Humboldt Foundation Researcher, Berlin, Germany.

2. LITERATURE REVIEW

2.1 Grain Size Effects

The particle size characteristics are another important factor that must be properly identified in the evaluation of the mechanical and hydraulic responses of granular materials (Monkul *et al.* 2011; Cherif Taiba *et al.* 2019b; Hazout *et al.* 2022). Monkul *et al.* (2011) indicated that as the ratio of the mean grain size ($D_{50\text{-sand}}/D_{50\text{-silt}}$) of the sand to silt particles was sufficiently small, the undrained shear strength of the sand increased steadily with the increase of silt fraction for the selected range (0% ~ 20%). When $D_{50\text{-sand}}/D_{50\text{-silt}}$ increased, the silty sand shear strength remained lesser than that of the clean sand. Lim *et al.* (2012) found that the particle size had a significant influence on the mechanical properties of sands. Janalizadeh *et al.* (2013) showed that the undrained cyclic resistance of the soil could be correlated to the granulometric grain sizes (D_{10}, D_{30}, or D_{60}) rather than the coefficient of uniformity (C_u) or coefficient of curvature (C_c) of the tested granular materials. Cherif Taiba *et al.* (2016) reported that the particle size significantly influenced the undrained shear resistance of sand-silt mixture samples. Wang *et al.* (2013) observed through a series of direct shear and triaxial tests found that the grain size characteristics had important effects on the internal friction angles of coarse-grained soils. Cherif Taiba *et al.* (2019a) found that the mobilized friction angles at instability and steady states decreased in a linear manner. Doumi *et al.* (2021) conducted a series of undrained compression tests using static triaxial apparatus to elucidate the influence of the relative effective diameter, ratio between effective diameter and maximum diameter (RED = D_{10}/D_{max}), on the shear resistance of partially saturated sands. They found that the RED had a remarkable impact on the shearing response of the tested sandy soils. As a result, they reported that the increase of the relative effective diameter induced a decrement of the ultimate shear strength of the partially saturated samples tested with the lower Skempton's pore pressure parameter (B = 20%) compared to the intermediate (B = 50%) and the highest (B = 90%) Skempton's pore pressure ones. Hazout *et al.* (2022) found that the maximum relative diameter, D_{max}/D_{50}, was a suitable parameter for predicting the maximum undrained shear strength, q_{max}, of the tested materials. Indeed, it decreased in a logarithmic manner with the increase of the maximum relative diameter for tested samples. Azaiez *et al.* (2022) reported that the particle size in terms of D_{10}, D_{50}, and C_u had noticeable effects on the unconfined compressive strength of coarse-grained soils mixed with fly ash material and the polyurethane organic polymer.

2.2 Fly Ash Effects

Published literature reported that fly ash has been found as the most effective material to enhance the compaction and shear strength characteristics of soft and expansive soils (Lo *et al.* 2002; Saied *et al.* 2012; Phanikumar *et al.* 2018; Nawagamuwa *et al.* 2018; Mogili *et al.* 2020; Simatupang *et al.* 2020; Anand and Sarkar 2021). Kermatikerman *et al.* (2017) conducted a series of cyclic triaxial tests on reconstituted sand-fly ash mixtures with a fly ash content ranging from 4% to 6% at an initial relative density (D_r = 20%). Three different confining pressures (50, 70, and 90 kPa) were considered. They found that the higher fly ash percentage mixtures, the lower liquefaction resistance susceptibility. Kermatikerman *et al.* (2018) reported that fly ash played an important role in increasing the undrained shear strength of coarse-grained soils, where they indicated that the undrained shear strength increased noticeably with the increase of fly ash content from 0% to 6% for the tested sand-fly ash mixtures. Kolay *et al.* (2019) reported that the fly ash material had multiple effects on the sand shear behaviors. They found that the addition of 10% fly ash content to clean sand induced a slight decrease in the liquefaction resistance. Beyond 10% fly ash, the liquefaction resistance improved significantly. Azaiez *et al.* (2021a) conducted a set of compaction and direct shear box tests on different granular classes of sand with distinct grain sizes mixed with fly ash material. They found that the fly ash had a remarkable effect on the compaction characteristics and the mechanical response of the sand-fly ash mixtures. Azaiez *et al.* (2021b) elucidated the correlation between the friction angle and the fly ash percentages through a series of direct shear box tests that were carried out on dense sand mixed with fly ash. They found that the fly ash induced a remarkable effect on the friction angle of the tested soils. They also reported that the peak friction angle, the maximum dilatancy angle, and the excess friction angle increased with the increase in fly ash content. They concluded that the sand mixed with fly ash could be considered as a reliable material in the sub-base layers and embankment construction.

On the other hand, a very limited researches have in the published literature to elucidate the effect of particle size characteristics on the mechanical performance of sand-fly ash binary assemblies. To achieve this goal, a series of direct shear box tests have been conducted on three granular classes derived from natural Chlef sand having three different minimum grain diameters ("CS-1" D_{min} = 0.08 mm, "CS-2" D_{min} = 0.63 mm and "CS-3" D_{min} = 2.00 mm) mixed with fly ash percentages (FA = 0%, 5%, 10%, and 15%). The dry funnel pluviated sand-fly ash mixture samples were reconstituted at an initial relative density of 28 ± 3%, then placed in direct shear box with 60 mm × 60 mm × 25 mm and subjected to three different normal stresses (σ_n = 100, 200, and 300 kPa).

3. EXPERIMENTAL PROGRAM

3.1 Index Properties of the Tested Materials

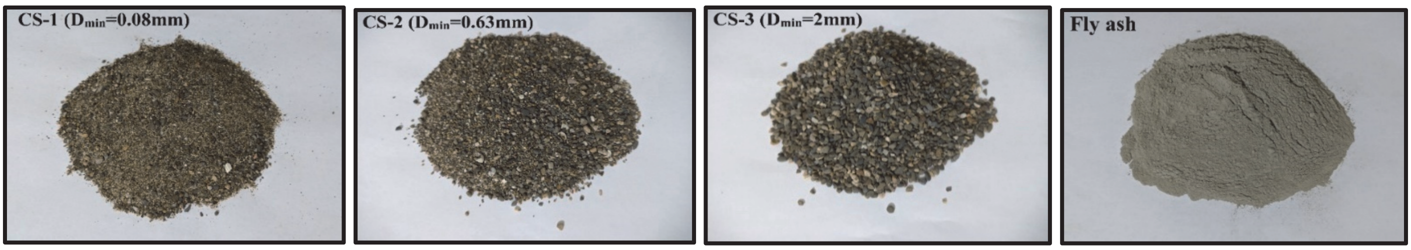
In addition to the fly ash that was brought from the Chlef cement plant, the poorly graded Chlef sand used in this experimental study was extracted from the banks of the Chlef river in the Oued Fodda area, located about 20 km east of center Chlef. Figure 1 presents the approximative location of Oued Fodda in Chlef, it has to be mentioned that Chlef provenance is situated approximately 200 km west of Algiers, the capital city of Algeria. The index characteristics of the various materials employed in this investigation are shown in Table 1. Three granular classes were used in the

Fig. 1 Location of Oued Fodda, Chlef, Algeria

Table 1 Index properties of the tested materials

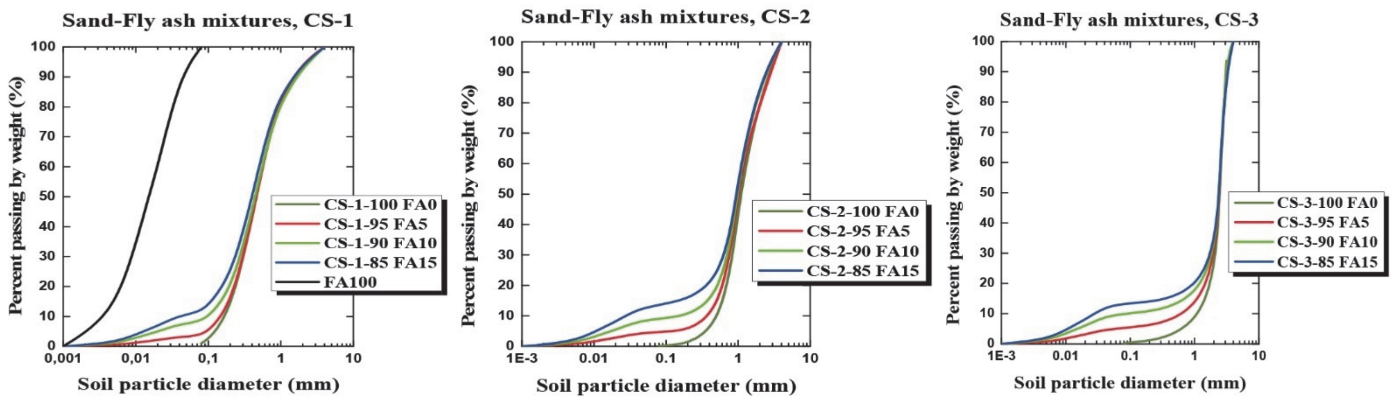
Sample	FA (%)	D_{max} (mm)	D_{min} (mm)	G_s	D_{10} (mm)	D_{30} (mm)	D_{50} (mm)	D_{60} (mm)	C_u	C_c	e_{max}	e_{min}
CS-1-100 FA0	0	4.000	0.080	2.660	0.180	0.345	0.498	0.574	3.199	1.158	0.750	0.507
CS-1-95 FA5	5			2.680	0.157	0.341	0.497	0.575	3.674	1.290	0.724	0.444
CS-1-90 FA10	10			2.700	0.100	0.311	0.483	0.569	5.674	1.692	0.704	0.397
CS-1-85 FA15	15			2,720	0.038	0.267	0.443	0.531	13.928	3.530	0.683	0.371
CS-2-100 FA0	0	4.000	0.630	2.670	0.694	0.854	1.055	1.350	1.945	0.778	0.808	0.610
CS-2-95 FA5	5			2.691	0.560	0.808	0.958	1.183	2.113	0.958	0.746	0.550
CS-2-90 FA10	10			2.710	0.276	0.781	0.946	1.118	4.051	1.977	0.724	0.496
CS-2-85 FA15	15			2.730	0.029	0.742	0.932	1.096	37.487	17.182	0.719	0.455
CS-3-100 FA0	0	4.000	2.000	2.680	2.063	2.254	2.446	2.575	1.248	0.956	0.851	0.648
CS-3-95 FA5	5			2.700	1.960	2.211	2.410	2.518	1.285	0.991	0.782	0.581
CS-3-90 FA10	10			2.720	1.500	2.183	2.399	2.512	1.675	1.265	0.730	0.520
CS-3-85 FA15	15			2.740	0.030	2.163	2.387	2.500	83.333	62.381	0.694	0.476
Fly ash	100	0.080	0.001	3.080	0.004	0.0009	0.015	0.020	4.444	0.900	2.114	0.914

present study. They have been derived from the Chlef natural sand according to their extreme grain diameters (D_{max} and D_{min},): CS-1 with a minimum grain diameter of 0.08 mm, CS-2 with a minimum grain diameter of 0.63 mm, and CS-3 with a minimum grain diameter of 2.00 mm. Figure 2 displays the materials that were used. The grain size distribution curves of the tested materials are shown in Fig. 3. The curves of grain size distribution were obtained by multiple sieve and hydrometer analysis following the ASTM C136-14 (2014) and ASTM D7928-17 (2017), respectively. Figure 3(a) represents the grain distribution curves corresponding to the category CS-1, which contains Chlef sand as a host sand with a minimum diameter of (D_{min} = 0.08 mm), and other mixtures of the same host sand but with different Fly ash contents (FA = 5%, 10%, and 15%), in addition to the curve of the pure fly ash. Figure 3(b) and Fig. 3(c) represent the distribution curves corresponding to the same host sand but with different minimum grain sizes (CS-2) and (CS-3). These two categories were also mixed with the same Fly ash proportions (FA= 5%,10%, and 15%). The maximum and minimum void ratios (e_{max}, e_{min}) were calculated according to ASTM D 4253 (2002) and ASTM D 4254 (2002) standards. The relationship between the void ratios and fly ash content is shown in Fig. 4. This figure shows that as the fly ash percentage increased up to 15%, the void ratios decreased.



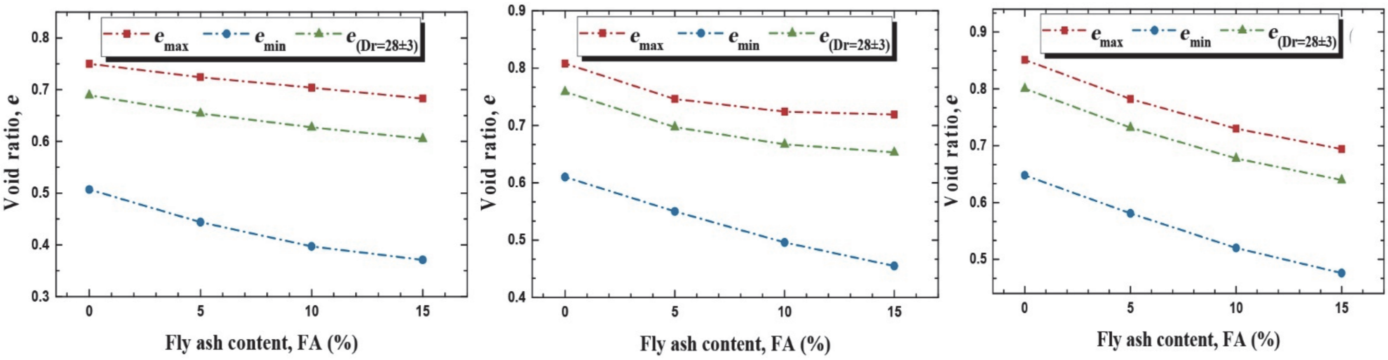
(a) (b) (c) (d)

Fig. 2 Granular classes derived from Chlef sand and fly ash



(a) CS-1 (b) CS-2 (c) CS-3

Fig. 3 Grain size distribution curves of the tested materials



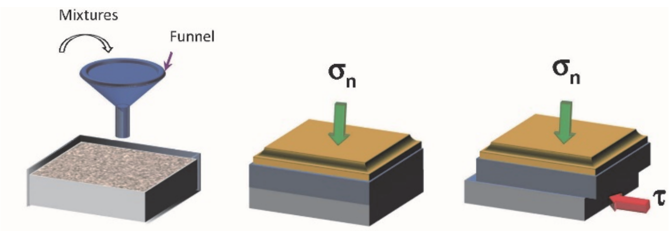
(a) D_{min} = 0.08 mm (b) D_{min} = 0.63 mm (c) D_{min} = 2.00 mm

Fig. 4 Void ratios versus fly ash content of the tested materials

3.2 Sample Preparation and Test Procedure

To evaluate the shear strength characteristics, a series of direct shear tests were performed in accordance with NF P94-071-1 (1994). Three granular classes were derived from the Chlef natural sand (CS-1, CS-2, and CS-3) were used in the experimental program, and these three binary combinations were produced by reconstituting the sand with fly ash components. Fly ash was mixed with the sand samples in quantities ranging from 0% to 15%. Using the dry pluviation process, the sand-fly ash mixture samples were created at an initial relative density of 28 ± 3%. This method consists of filling the box of the apparatus by raining the dry sand-fly ash mixture through the funnel by controlling the height (Fig. 5). A cross section through a typical direct shear device is shown in Fig. 6. The soil sample has a porous stone at the top and bottom to allow free drainage. Above the upper stone is a metal loading cap which is, in turn, subjected to the normal force. The sample and rings were mounted in a tank. The shearing force was applied to the outside of the tank, which was on rollers and the size of the box is 60 mm by 60 mm by 25 mm. After that, the binary mixes were placed in the box using a funnel to determine the suggested starting loose relative density, therefore, all the other necessary adjustments were made. Beyond that, the sand-fly ash mixtures take square plates form that were subsequently subjected to three normal stresses (σ_n =100, 200, and 300 kPa). All tests were carried out at a constant speed of 1 mm/min. The procedure was repeated three times for each test. After this stage, the data were collected from the computer which was connected directly with direct shear apparatus. Equation (1) was used to determine the sample mass according to Sadrekarimi and Olson (2012), Sze *et al.* (2014), and Mahmoudi *et al.* (2019, 2022):

$$m_s = (V_T \times \gamma_s) / [1 + e_{max} \times (1 - D_r) + D_r \times e_{min}] \quad (1)$$



(a) (b) (c)

Fig. 5 Steps of direct shear box test

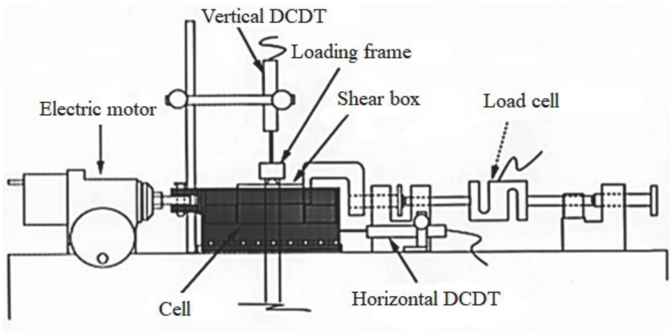


Fig. 6 Schematic drawing of direct shear apparatus

4. RESULTS AND DISCUSSION

4.1 Particle Size Effects

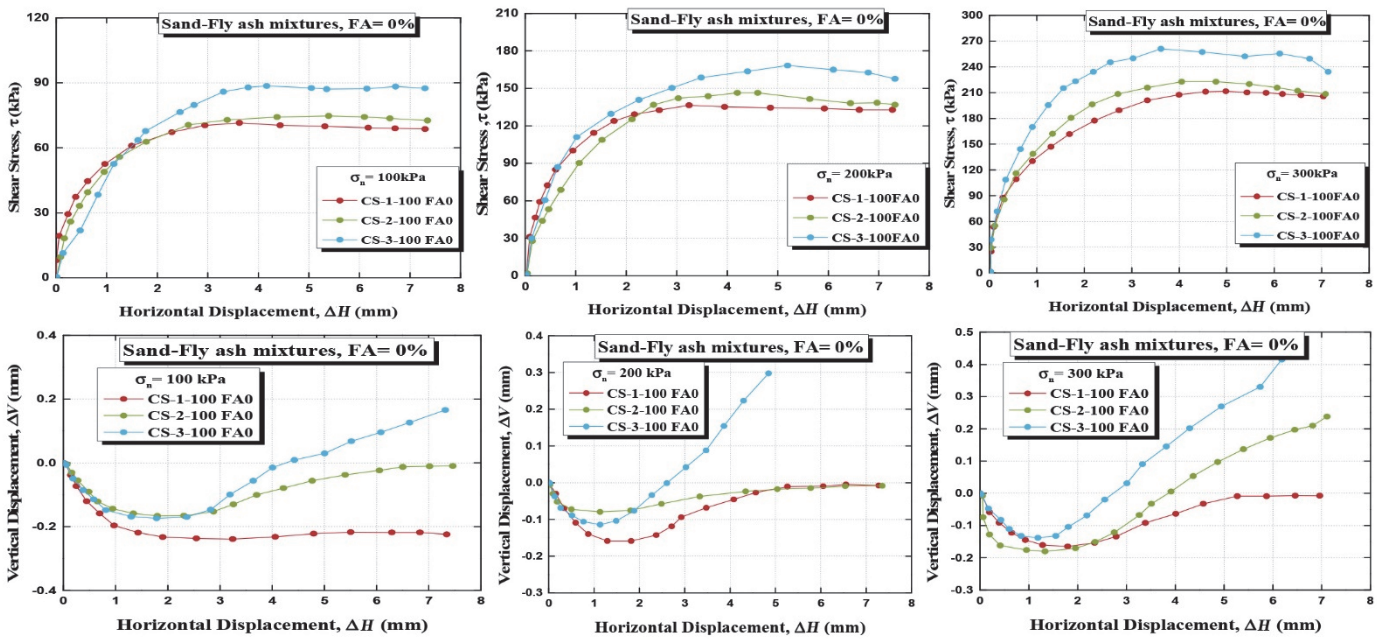
To assess the impact of particle size on the mechanical behavior of the sand-fly ash mixtures (FA = 5%, 10%, and 15%), the samples were subjected to three initial normal stresses, σ_n = 100, 200, and 300 kPa, after being prepared with a loose relative density (D_r = 28 ± 3%). Overall, the results indicate that the minimum grain diameter (D_{min}) has a very significant impact on the mechanical performance of the sand-fly ash mixtures. As can be seen, increasing the minimum grain diameter generally results in an increase in the shear strength of the tested materials. However, the effect of D_{min} on increasing the shear response can be clearly seen for the range of 0.08 mm ~ 0.63 mm of minimum grain diameters (Figs. 7(a), 8(a), 9(a), and 10(a)). Additionally, the results obtained for the normal stress of σ_n = 200 kPa show that the samples of mixtures with D_{min} = 2.00 mm exhibit high shear strength values in comparison to those of D_{min} = 0.63 mm mixtures and become very pronounced for the binary assemblies of D_{min} = 0.08 mm (Figs. 7(b), 8(b), 9(b), and 10(b)).

On the other hand, the shear resistance values of the sand-fly ash mixtures subjected to a normal stress of σ_n = 300 kPa are higher than those of σ_n = 100 and 200 kPa. In comparison to the binary matrix of CS-2 mm and CS-1, the samples of the sand-fly ash mixtures with CS-3 show a remarkable increase in the maximum shear strength for the fractions (FA = 0%, 5%, 10%, and 15%) (Figs. 7(c), 8(c), 9(c), and 10(c)). The right side of the diagram illustrates the evolution of the vertical displacement as a function of the horizontal displacement while taking into account the impact of the minimum grain diameter (Figs. 7 to 10). The outcomes support the minimum grain diameter parameter's role in the progression of the dilatancy phase with increasing values of the minimum grain diameter.

4.2 Fly Ash Effects

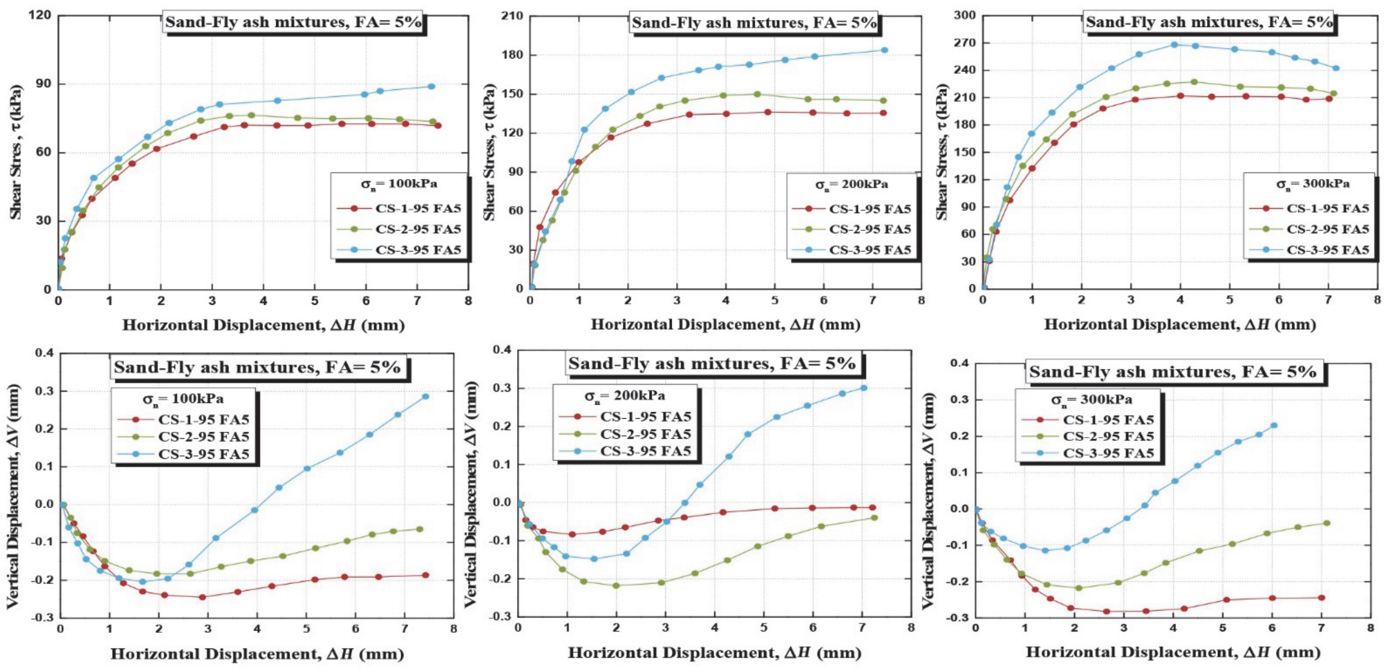
The dry pluviated samples were subjected to three initial normal stresses (σ_n = 100, 200, and 300 kPa), and the evolution of shear stress as a function of horizontal displacement was plotted for the first categories mixed in the range of FA = 0% to FA = 15%, as shown in Fig. 11. Overall, the increase in FA content had a positive effect on the residual shear strength of the mixture.

The evolution of shear stress *vs.* horizontal displacement for the second type of mixtures is shown in Fig. 12. In general, the recorded data shows that an increase in the FA content may have a significant impact on soil mechanical behavior, since any increase in FA increases the residual shear strength of the tested



(a) σ_n = 100 kPa (b) σ_n = 200 kPa (c) σ_n = 300 kPa

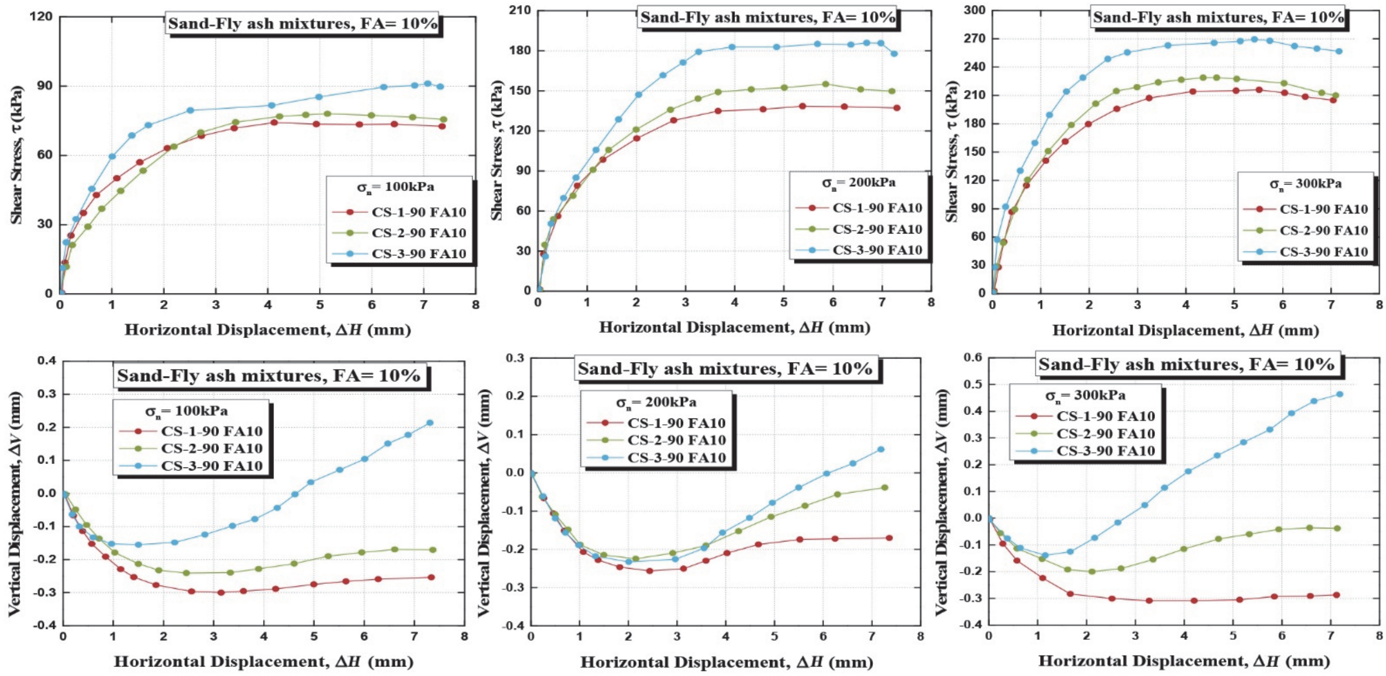
Fig. 7 Influence of minimum grain diameter on the shear stress variation of Chlef sand (FA = 0%)



(a) σ_n = 100 kPa (b) σ_n = 200 kPa (c) σ_n = 300 kPa

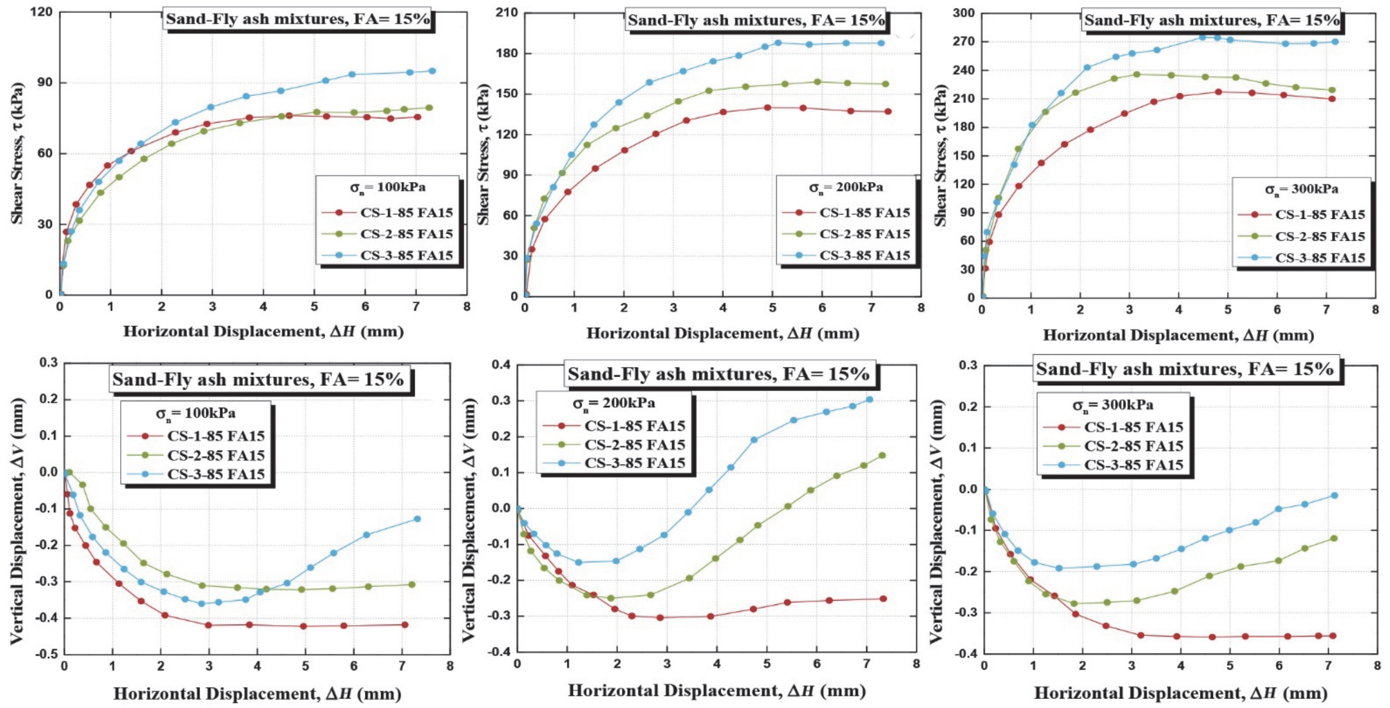
Fig. 8 Influence of minimum grain diameter on the shear stress variation of Chlef sand-fly ash mixtures (FA = 5%)

materials. On the other hand, Fig. 13 shows the shear stress *vs.* the horizontal displacement for the third type of the sand-fly ash binary assemblies. The resulting Figures clearly show that the addition of fly ash has a significant impact on the residual shear strength for the entire mixtures. The use of FA improved the interparticle locking between coarse sand grains, resulting in increased shear strength. These findings are in good agreement with the observations of Kolay *et al.* (2019) and Azaiez *et al.* (2021a, 2021b).



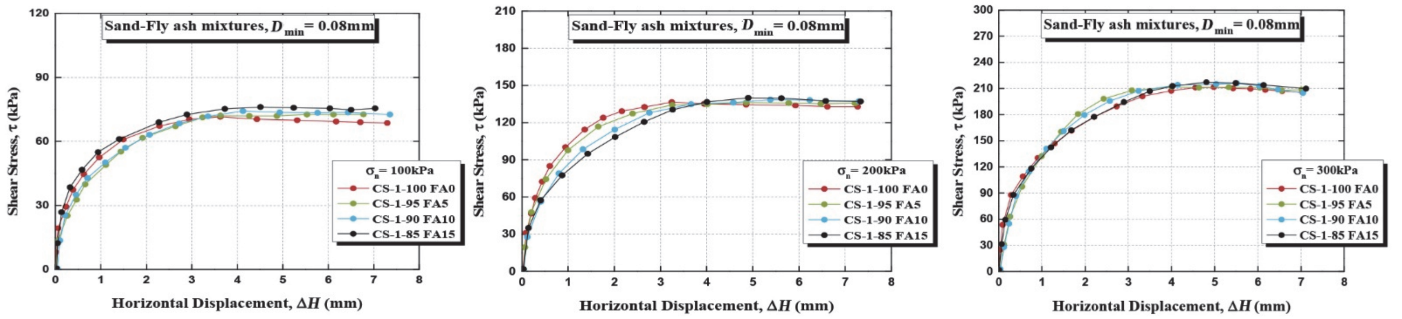
(a) σ_n = 100 kPa (b) σ_n = 200 kPa, (c) σ_n = 300 kPa

Fig. 9 Influence of minimum grain diameter on the shear stress variations of Chlef sand-fly ash mixtures (FA = 10%)



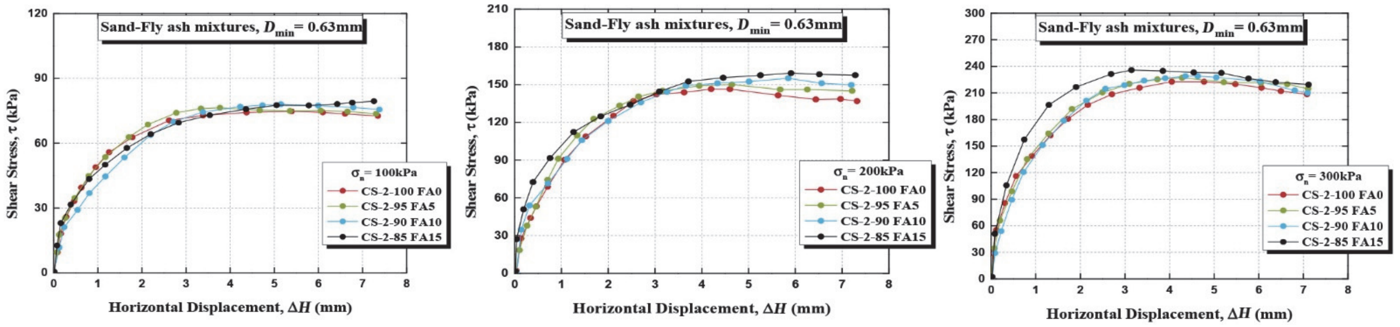
(a) σ_n = 100 kPa (b) σ_n = 200 kPa (c) σ_n = 300 kPa

Fig. 10 Influence of minimum grain diameter on the shear stress variation of Chlef sand-fly ash mixtures (FA = 15%)



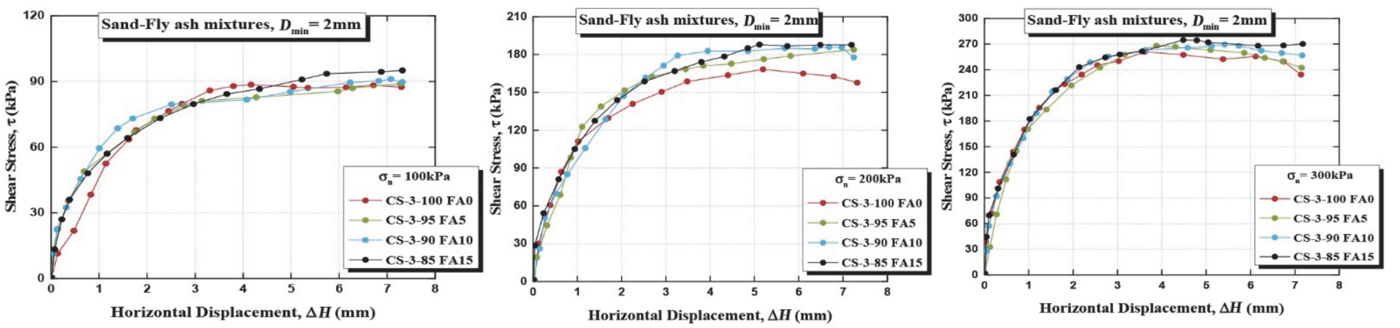
(a) σ_n = 100 kPa (b) σ_n = 200 kPa (c) σ_n = 300 kPa

Fig. 11 Shear stress versus horizontal displacement of Chlef sand-fly ash mixtures, CS-1 (D_{min} = 0.08 mm)



(a) σ_n = 100 kPa (b) σ_n = 200 kPa (c) σ_n = 300 kPa

Fig. 12 Shear stress versus horizontal displacement of Chlef sand-fly ash mixtures, CS-2 (D_{min} = 0.63mm)



(a) σ_n = 100 kPa (b) σ_n = 200 kPa (c) σ_n = 300 kPa

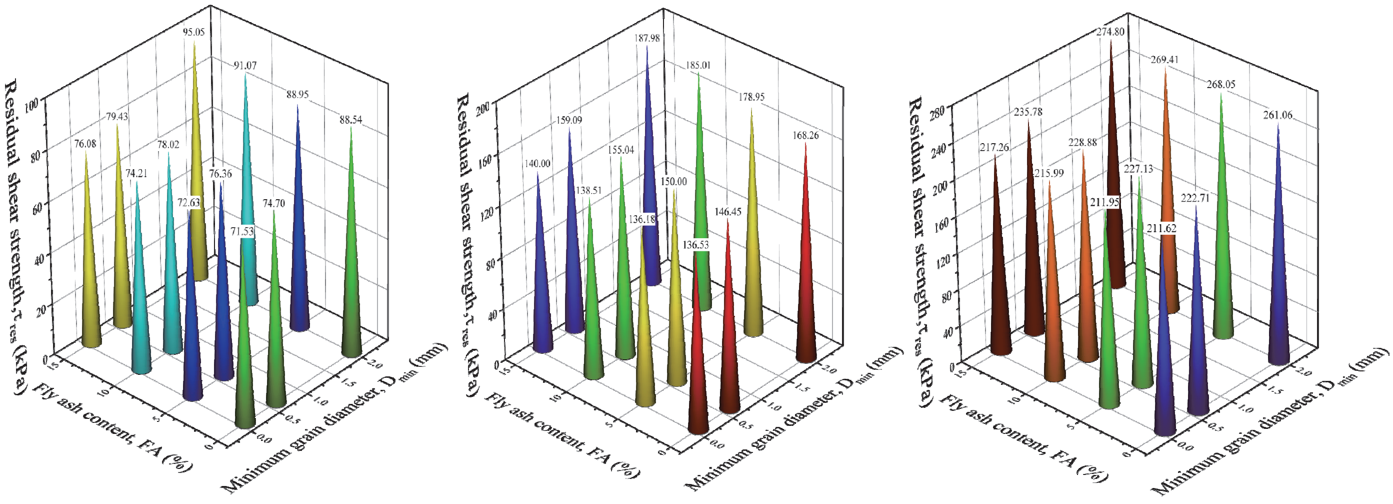
Fig. 13 Shear stress versus horizontal displacement of Chlef sand-fly ash mixtures, CS-3 (D_{min} = 2.00 mm)

4.3 Correlation Between the Residual Shear Strength (τ_{res}) with the Minimum Grain Diameter (D_{min}) and Fly Ash Content (FA)

Figure 14 demonstrates that under the applied initial normal stress (σ_n =100, 200, and 300 kPa), there are strong correlations between the residual shear strength with the minimum grain diameter, and the fly ash content of the materials under study. It is clearly shown that the residual shear strength (τ_{res}) rises, with both the minimum grain diameter and the fly ash percentages (D_{min} and FA). Additionally, compared to the first and second normal stresses (σ_n =100 and 200 kPa, respectively), this tendency is more appropriate and substantial for the third initial normal stress (σ_n =300 kPa). This result demonstrates that assessing the correlation between these indicators depends on the typical stress level. The observed direct shear response of the various binary combinations is explained by the fact that the studied sand-fly ash mixtures were denser as the fly ash fraction rose, which made it simpler for particles of the right size to migrate and orient themselves. These results generally support the notion that the fly ash content and the minimum grain diameter are important factors in enhancing the shear resistance of the binary assemblies for geotechnical engineering applications.

4.4 Mechanical Characteristics (ϕ, *I*) versus Minimum Grain Diameter (D_{min}) and Fly Ash Content (FA)

Figure 15 illustrates the variation of mechanical characteristics in terms of internal friction angle and interlocking (ϕ, *I*) with the minimum grain diameter (D_{min}) and fly ash fraction (FA) of

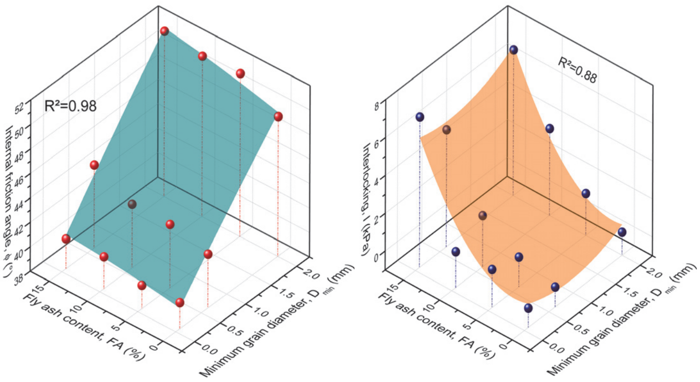


(a) σ_n = 100 kPa (b) σ_n = 200 kPa (c) σ_n = 300 kPa

Fig. 14 Residual shear strength versus minimum grain diameter and fly ash content of the tested materials

Table 2 Values of the coefficients *a*, *b*, *c*, *d*, *f*, *z* and R^2 corresponding in Eqs. (2) and (3)

	Equation (2)	Equation (3)
a	5.53	–1.31
b	0.10	–0.14
c	–0.14	0.72
d	–0.0022	0.034
f	0.034	0.024
z	39.25	0.36
R^2	0.98	0.88



(a) Internal friction angle (b) Interlocking

Fig. 15 Variation of mechanical characteristics versus minimum grain diameter and fly ash content of the tested materials

three binary granular mixtures. For the interlocking parameter, it is generally believed that the cohesion characteristic in cohesionless soil does not exist (De Mello 1977; Indraratna *et al.* 1993; Wang *et al.* 2019). However, a large laboratory tests have proven that cohesionless soil has interlocking strength due to the effects of interlocking and occlusion contact. The shear strength of granular soil is a comprehensive reflection of friction effect and interlocking effect. The interlocking strength is also the intercept of the tangential line of the Coulomb curve representing the relationship between shear stress and normal strength (the intrinsic line or the Coulomb line). Moreover, for all employed materials taken into consideration, it appears that the fitting surface could effectively capture the association between the internal friction angle and interlocking with the fly ash content and minimum grain diameter with ($R^2 = 0.98$ and $R^2 = 0.88$). Additionally, the results show that increasing the minimum grain diameter (D_{min} = 0.08 to 2.00 mm) and the fly ash content (FA = 0% to FA = 15%) both significantly increase the internal friction angle of the studied mixtures. Moreover, the test results clearly show that the internal friction angle between the mixtures of CS-2 and CS-3 increased significantly when compared to those of the mixtures ranging between CS-1 and CS-2 (Fig. 15(a)). This tendency demonstrates that the increment of the internal friction angle of the tested sand-fly ash mixture samples depends significantly on the particle size characteristic.

On the other hand, Fig. 15(b) illustrates clearly the relationship between the interlocking (*I*) with fly ash content (FA) and minimum grain diameter (D_{min}) of the tested sand-fly ash mixtures. The obtained results indicate that the minimum grain diameter and fly ash addition affects significantly the soil tendency, inducing an important increase of the interlocking. This pattern might be explained by the involvement of fly ash particles filling the spaces between sand grains, increasing interparticle forces, and improving interlocking. In order to forecast the fluctuation of the internal friction angle and the interlocking (*I*) as a function of the minimum grain diameter (D_{min}) and fly ash content (FA) of the investigated materials, the following Eqs. (2) and (3) are proposed:

$$\phi = a \times (D_{min}) + b \times (\mathrm{FA}) + c \times (D_{min})^2 + d \times (\mathrm{FA})^2 + f \times (D_{min}) \times (\mathrm{FA}) + z \quad (2)$$

$$I = a \times (D_{min}) + b \times (\mathrm{FA}) + c \times (D_{min})^2 + d \times (\mathrm{FA})^2 + f \times (D_{min}) \times (\mathrm{FA}) + z \quad (3)$$

4.5 Influence of the Minimum Grain Diameter and Fly Ash Content on the Peak Friction Angle

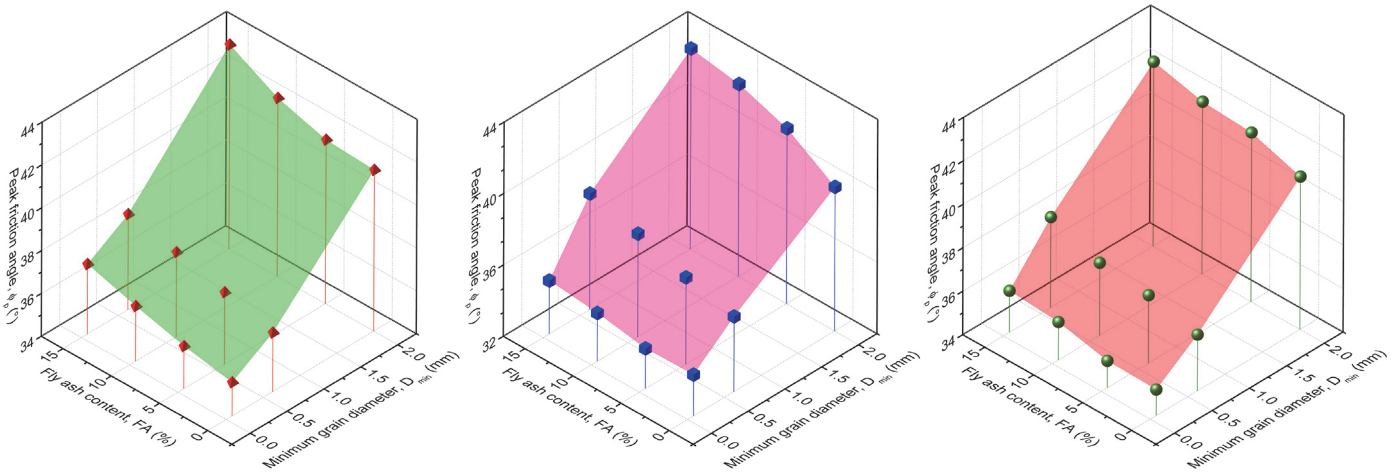
The 3D plots shown in Fig. 16 were used to describe the correlation between the peak friction angle (ϕ_p) the minimum grain diameter, and fly ash content. The obtained findings clearly show that, for the entire studied assemblies, the peak friction angle could correlate extremely well with the minimum grain diameter and fly ash percentages. According to test results, increasing the minimum grain diameter could result in a boost of peak friction angle. It is clear that changing the minimum grain diameter has a significant impact on the peak friction angle. Additionally, the peak friction angle show an increasing trend with addition of FA. The FA particles' filling the spaces between the coarse sand particles decreased the void ratio within the mixture structures, and consequently increased the peak friction angle of the mixtures under consideration.

4.6 Influence of the Minimum Grain Diameter and Fly Ash Content on the Shear Strength Enhancement Factor

The shear strength enhancement (FSE) is a new factor used in this study to quantify the impact made by certain parameters on the shear strength of the studied soil. It is defined as the ratio of the residual shear strength of the mixture to that of the pure sand according to the following equation:

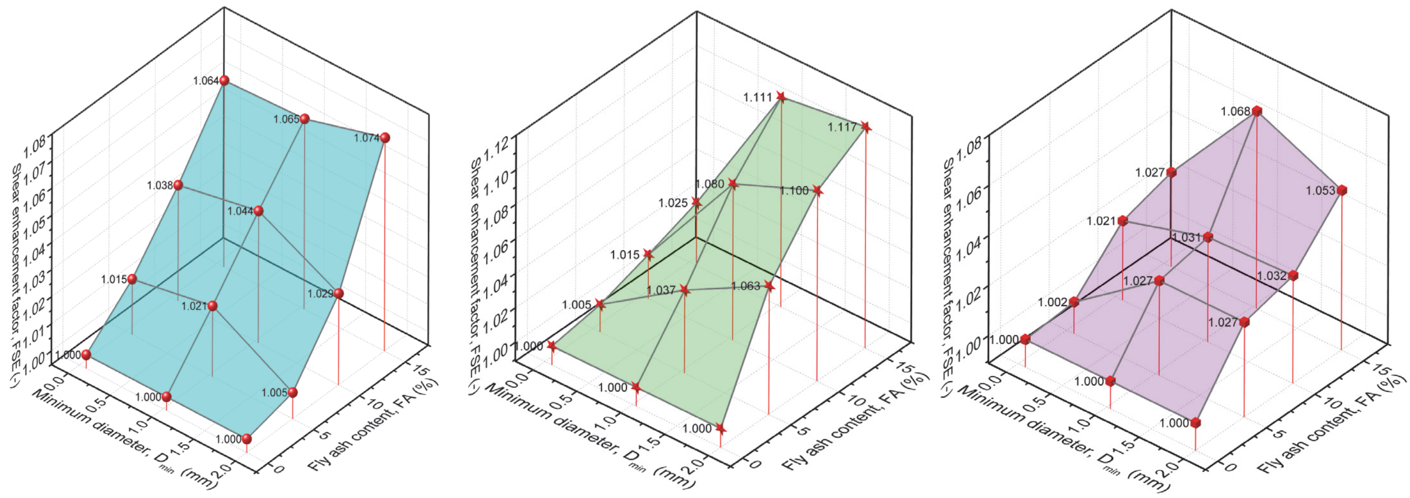
$$\mathrm{FSE} = \frac{\tau_{\mathrm{res \cdot mixtures}}}{\tau_{\mathrm{res \cdot sand}}} \tag{4}$$

The effect of fly ash content and minimum grain diameter on the FSE of the tested binary mixes is shown in Fig. 17. It is evident that the minimum grain diameter and fly ash content have a significant impact on the FSE. Whereas, for the various evaluated grades of sand, an increase in the fly ash percentages leads to an increase in the FSE. However, compared to the other binary assemblies, the fly ash percentage of FA = 15% exhibits higher values of FSE. These observations clearly show that the increased in the recommended parameter (FSE) for the studied sand-fly ash mixes was influenced by the larger amount of fly ash.



(a) σ_n = 100 kPa (b) σ_n = 200 kPa (c) σ_n = 300 kPa

Fig. 16 Peak friction angle as function of minimum grain diameter and fly ash content of the examined mixtures



(a) σ_n = 100 kPa (b) σ_n = 200 kPa (c) σ_n =300 kPa

Fig. 17 Shear enhancement factor versus fly ash content and minimum grain diameter

4.7 Influence of the Particle Size Index and Fly Ash Content on the Internal and Peak Friction Angles

In order to specifically highlight the relationship between particle size index, fly ash portions, and the friction angle of the tested materials, Fig. 18 shows the variation of the internal friction angle as a function of the newly introduced parameter, named particle size index (PSI), which can be evaluated as follows:

$$PSI = \frac{(D_{max} - D_{min})}{D_{50}} \quad (5)$$

where D_{max} is the maximal grain diameter ($D_{max} = 4.00$ mm) for the studied material, D_{min} and D_{50} are the minimum and mean grain diameters, respectively. It is clear that the internal friction angle of the sand-fly ash mixtures is significantly influenced by the PSI. Additionally, the internal friction angle of the employed materials under consideration significantly increases as the PSI decreases. Furthermore, it is evident from these plots that the sand-fly ash mixture samples displayed stronger resistance at lower PSI values due to increased internal friction angles. As expected, these three parameters were nicely correlated (with the coefficient of determination $R^2 = 0.99$), so the increase in PSI leads to a significantly lower

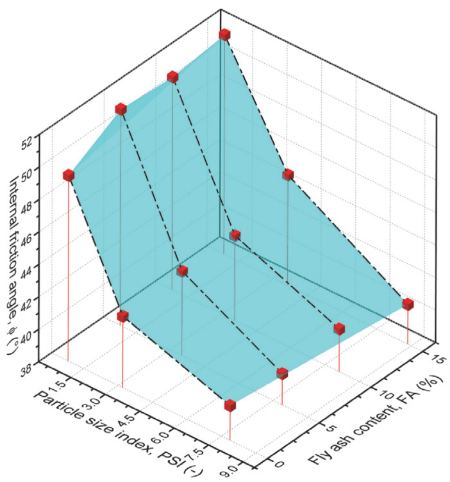


Fig. 18 Internal friction angle variations against fly ash content and particle size index of the studied mixtures

peak friction angle for the tested initial normal stresses ($\sigma_n = 100$, 200, and 300 kPa). On the other hand, the evolution of peak friction angle against both particle size index and fly ash content is illustrated in Fig. 19. Additionally, the 3D plots indicate that the tested binary assemblies' peak friction angles were lower at larger values of the PSI. For the sand-fly ash mixtures, the correlation between the peak friction angle, PSI, and FA content may be assessed using the following expression.

$$\phi_p = a \times (PSI) + b \times (FA) + c \times (PSI)^2 + d \times (FA) + f \times (PSI) \times (FA) + z \quad (6)$$

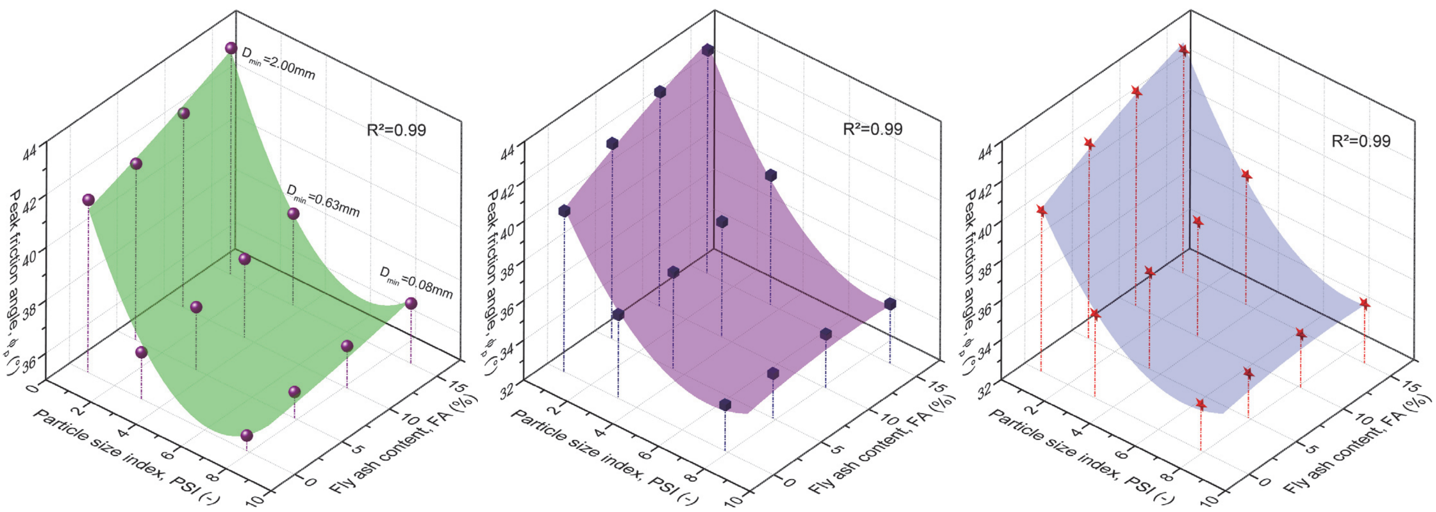
Table 3 illustrates the coefficients a, b, c, d, f and z and the corresponding coefficient of determination (R^2) for the materials under consideration.

Table 3 Values of coefficients *a*, *b*, *c*, *d*, *e*, *f* and R^2 in Eq. (6)

	$\sigma_n = 100$ kPa	$\sigma_n = 200$ kPa	$\sigma_n = 300$ kPa
a	−2.51	−2.25	−2.36
b	0.14	0.31	0.15
c	0.20	0.16	0.18
d	0.002	−0.004	−0.002
f	−0.01	−0.024	−0.01
z	43.08	41.93	42.69
R^2	0.99	0.99	0.99

4.8 Correlation Between the Particle Size Index (PSI) and the Shear Strength Enhancement Factor (FSE)

The relationship between the PSI and FSE of sand-fly ash mixes is shown in Fig. 20. The particle size index may be used as a suitable measure to forecast the FSE of the tested soil samples, as illustrated in the plot. In reality, for the chosen materials, the FSE rises as PSI rises, and a strong correlation may exist between the two properties of the sand-fly ash binary matrix subjected to the initial normal stresses ($\sigma_n = 100$, 200, and 300 kPa). Additionally, according to the test results, the third category of sand and fly ash mixtures showed higher values of the FSE than the second category of sand and the first category of sand and fly ash mixtures. In contrast, to reconstituted mixtures made from medium and finer sand particles ($D_{min} = 0.63$ and 0.08 mm) with the fly ash material



(a) $\sigma_n = 100$ kPa (b) $\sigma_n = 200$ kPa (c) $\sigma_n = 300$ kPa

Fig. 19 Peak friction angle versus fly ash content and particle size index of the mixtures under study

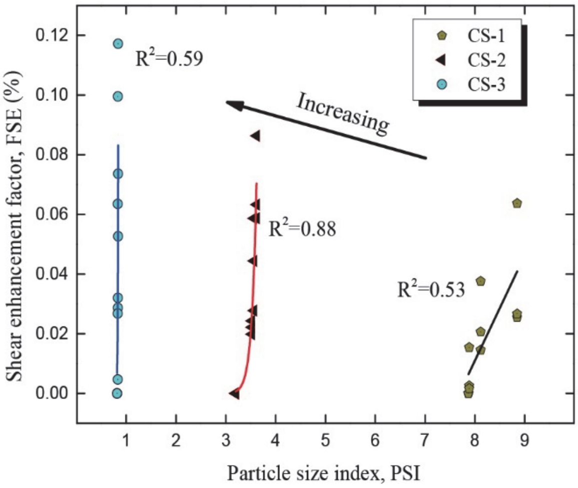


Fig. 20 Shear enhancement factor versus particle size index of the examined mixtures

under consideration, this tendency confirms that coarser sand particles (D_{min} = 2.00 mm) mixed with the fly ash materials were the cause of the decreasing of the particle size index of mixtures leading to the increase of the FSE of these mixtures. This result demonstrates that the sample grading in terms of particle size index is effective in predicting and assessing the mechanical behavior of the samples of the sand-fly ash mixture under study. The FSE and PSI of the tested materials are suggested to be related using the following equations:

For CS-1 (D_{min} = 0.08 mm): $FSE = a + b \times (PSI)$ (7)

For CS-2 (D_{min} = 0.63 mm): $FSE = a \times (PSI)^b$ (8)

For CS-3 (D_{min} = 2.00 mm): $FSE = a \times (PSI)^b$ (9)

Table 4 shows the values of the coefficients a, b and R^2 for the Eqs. (7), (8), and (9) corresponding to the samples CS-1 (D_{min} = 0.08 mm), CS-2 (D_{min} = 0.63 mm), and CS-3 (D_{min} = 2.00 mm) respectively.

Table 4 Values of coefficients *a*, *b* and R^2 in Eqs. (7) ~ (9)

	Equation (7)	Equation (8)	Equation (9)
a	–0.27	7.29233×10^{-23}	6.4395×10^{6}
b	0.035	37.59	102.7
R^2	0.53	0.88	0.55

5. CONCLUSIONS

The study investigates the influences of particle size in terms of the maximum grain diameter (D_{min}) and the particle size index (PSI), as well as the fly ash content (FA), on the shear properties of untreated and treated sandy sample with fly ash percentages. The main findings are as follows:

1. The results indicate that the minimum grain diameter (D_{min}) is a pertinent parameter to control the mechanical response of the examined mixtures. Coarser particles (D_{min} = 2.00 mm) enhance the residual shear strength (τ_{res}) of the sand-fly ash mixtures. In fact, the increase of the minimum grain diameter (D_{min} = 0.08 to 0.63 mm) induces a noticeable increase in the shear strength of the sand-fly ash binary assemblies for all considered initial conditions.
2. The variation of the fly ash percentages has a significant impact on the residual shear strength (τ_{res}) and the mechanical characteristics (friction angle, ϕ, and interlocking, I). These characteristics increase with the increase of fly ash fraction for all tested parameters. Consequently, the increase of the shear characteristics, ϕ and I, leads to a more stable sand-fly ash mixture sample structure. Moreover, the peak friction angle, ϕ_p, increases with the increase of the minimum grain diameter (D_{min} = 0.08, 0.63, and 2.00 mm) and the used fly ash contents (FA = 0%, 5%, 10%, and 15%) for the studied binary mixtures subjected to three initial normal stresses (σ_n = 100, 200, and 300 kPa).
3. Two new parameters are proposed in this paper to evaluate the effectiveness of fly ash material on the mechanical performance of the tested sand-fly ash mixture samples (FSE and PSI). The analysis of the results indicates that the FSE correlates very well with the minimum grain diameter and the fly ash content as well as the PSI with the internal and peak friction angle of the sand-fly ash binary mixtures.
4. Finally, the outcome of this laboratory investigation confirms that the shear strength enhancement factor correlates very well with the particle size index, where, the FSE increases as PSI increases for all tested mixtures. These findings explain clearly that the sample grading in terms of particle size index plays a remarkable role in the prediction and evaluation of the mechanical performance of sand-fly ash binary assemblies under the consideration. Based on the results of this research, the use of fly ash is highly recommended for enhancing the shear properties of soils in many geotechnical engineering applications.

ACKNOWLEDGMENTS

This research work was carried out in the Laboratory of Materials Sciences & Environment at Hassiba Benbouali University of Chlef (Algeria). The authors are thankful to all those who effectively contributed to the achievement of this laboratory investigation.

FUNDING

The authors are grateful for the financial support received from the Directorate General for Scientific Research and Technological Development, Ministry of Higher Education and Scientific Research of Algeria.

DATA AVAILABILITY

The authors declared that all data are included in the manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

NOTATIONS

C_c	coefficient of curvature
C_u	coefficient of uniformity
D_{10}	effective particle size (mm)
D_{30}	particle size corresponding to 30% passing by weight (mm)
D_{50}	mean particle size (mm)
D_{60}	particle size corresponding to 60% passing by weight (mm)
D_{max}	maximum grain diameter (mm)
D_{min}	minimum grain diameter (mm)
D_r	relative density (%)
e	index void ratio
e_{max}	maximum void ratio
e_{min}	minimum void ratio
FA	fly ash content (%)
FSE	shear strength enhancement factor
G_s	specific gravity
ΔH	horizontal displacement (mm)
I	interlocking (kPa)
PSI	particle size index
ΔV	vertical displacement (mm)
ϕ	internal friction angle (°)
ϕ_p	peak friction angle (°)
σ_n	normal stress (kPa)
τ	shear stress (kPa)
τ_{res}	residual shear strength (kPa)

REFERENCES

Alshibli, K.A. and Mehmet, B.C. (2018). "Influence of particle morphology on the friction and dilatancy of sand." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, **144**(3), 04017118. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001841

Anand, A. and Sarkar, R.A. (2021). "Comprehensive study on bearing behaviour of cement-fly ash composites through experimental and probabilistic investigations." *Innovative Infrastructure Solutions*, **6**(39). https://doi.org/10.1007/s41062-020-00404-w

ASTM D 4253-00 (2002). *Standard Test Method for Maximum Index Density and Unit Weight of Soils using a Vibratory Table*. Annual Book of ASTM Standards. American Society for Testing and Materials, West Conshohocken, PA, 1-14.

ASTM D 4254-00 (2002). *Standard Test Method for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density*. Annual Book of ASTM Standards. American Society for Testing and Materials, West Conshohocken, PA, 1-9.

ASTM C136-14 (2014). *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*. Annual Book of ASTM Standards. American Society for Testing and Materials. https://doi.org/10.1520/C0136_C0136M-14

ASTM D7928-17 (2017). *Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils using the Sedimentation (Hydrometer) Analysis*. Annual Book of ASTM Standards. American Society for Testing and Materials. https://doi.org/10.1520/D7928-17

Azaiez, H., Cherif Taiba, A., Mahmoudi, Y., and Belkhatir, M., (2021). "Shear characteristics of fly ash improved sand as an embankment material for road infrastructure purpose." *Innovative Infrastructure Solutions*, **6**(148). https://doi.org/10.1007/s41062-021-00517-w

Azaiez, H., Cherif Taiba, A., Mahmoudi, Y., and Belkhatir, M. (2021). "Characterization of granular materials treated with fly ash for road infrastructure applications." *Transportation Infrastructure Geotechnology*, **8**, 228-253. https://doi.org/10.1007/s40515-020-00135-6

Azaiez, H., Cherif Taiba, A., Mahmoudi, Y., and Belkhatir, M. (2022). "Polyurethane organic polymer as an eco-friendly solution for improvement of shear strength of sand-fly ash mixtures." *Journal of GeoEngineering*, **17**(2), 103-112. https://doi.org/10.6310/jog.202206_17(2).4

Borhani, A. and Fakharian, K. (2016). "Effect of particle shape on dilative behavior and stress path characteristics of Chamkhaleh sand in undrained Triaxial tests." *International Journal of Civil Engineering*, **14**(4), 197-208. https://doi.org/10.1007/s40999-016-0048-8

Cherif Taiba, A., Mahmoudi, Y., Belkhatir, M., Kadri, A., and Schanz, T. (2016). "Insight into the effect of granulometric characteristics on static liquefation sucseptibility of silty sand soils." *Geotechnical and Geological Engineering*. https://doi.org/10.1007/s10706-015-9951-z

Cherif Taiba, A., Mahmoudi, Y., Belkhatir, M., Kadri, A., and Tom Schanz, T. (2017). "Experimental characterization of the undrained instability and steady state of silty sand soils under monotonic loading conditions." *International Journal of Geotechnical Engineering*. https://doi.org/10.1080 /19386362.2017.1302643

Cherif Taiba, A., Mahmoudi, Y., Belkhatir, M., and Schanz, T. (2018). "Experimental investigation into the influence of roundness and sphericity on the undrained shear response of silty sand soils." *Geotechnical Testing Journal*. https://doi.org/10.1520/GTJ20170118

Cherif Taiba, A., Mahmoudi, Y., Hazout, L., Belkhatir, M., and Baille, W. (2019a). "Evaluation of hydraulic conductivity through particle shape and packing density characteristics of sand–silt mixtures." *Marine Georesources & Geotechnology*, 1-13. https://doi.org/10.1080/1064119x.2018.1539891

Cherif Taiba, A., Mahmoudi, Y., Hazout, L., Belkhatir, M., and Baille, W. (2019b). "Effects of gradation on the mobilized friction angle for the instability and steady states of sand-silt mixtures: Experimental Evidence." *Acta Geotechnica Slovenica*. https://doi.org/10.18690/actageotechslov.16.1.79-95

Cherif Taiba, A., Mahmoudi, Y., Baille, W., Wichtmann, T., and Belkhatir, M. (2021). "Threshold silt content dependency on particle morphology (shape and size) of granular materials: review with new evidence." *Acta Geotechnica Slovenica*, **18**(1), 28-40. https://doi.org/10.18690/actageotechslov.18.1.28-40.2021

Cherif Taiba, A., Mahmoudi, Y., Azaiez, H., and Belkhatir, M. (2022). "Impact of the overall regularity and related granulometric characteristics on the critical state soil mechanics of natural sands: A state-of-the-art review." *Geomechanics and Geoengineering*. https://doi.org/10.1080/17486025.2022.2044076

De Mello, V.F.B. (1977). “Reflection on decisions of practical significance to embankment dam constitution: 17th rankine lecture.” *Geotechnique*, **27**(3), 281-355. https://doi.org/10.5772/intechopen.92745

Doumi, K., Mahmoudi, Y., Cherif Taiba, A., Belkhatir, M., and Baille, W. (2021). “Experimental investigation on the influence of relative effective diameter on ultimate shear strength of partially saturated granular soils.” *Acta geotechnica Slovenica*, **17**(1), 56-70. https://doi.org/10.18690/actageotechslov.17.1.56-70.2020

Janalizadeh, C., A., Ghalandarzadeh, A., and Esmaeili, M. (2013). “Experimental study of the grading characteristic effect on liquefaction resistance of various graded sands and gravelly sands.” *Arabian Journal of Geosciences*. https://doi.org/10.1007/s12517-013-0886-5

Hazout, L., Cherif Taiba, A., Mahmoudi, Y., and Belkhatir, M. (2022). “Deformation characteristics of natural river sand under compression loading incorporating extreme particle diameters impacts.” *Marine Georesources & Geotechnology*. https://doi.org/10.1080/1064119X.2022.2122090

Indraratna, B., Wijewardena, L.S.S., and Balasubramaniam, A.S. (1993). “Large-scale triaxial testing of greywacke rockfill.” *Géotechnique*, **43**(1), 37-51. https://doi.org/10.1680/geot.1993.43.1.37

Kermatikeman, M., Chegenizadeh, A., Nikraz, H., Ayad Salih Sabbar (2017). “Experimental study on effect of fly ash on liquefaction resistance of sand.” *Soil Dynamics and Earthquake Engineering*, **93**, 1-6. https://doi.org/10.1016/j.soildyn.2016.11.012

Keramatikerman, M., Chegenizadeh, A., and Nikraz, H. (2018). “Effect of fly ash on post cyclic behavior of sand.” *Journal of Earthquake Engineering*. ISSN: 1363-2469 (Print) 1559-808X. https://doi.org10.1080/13632469.2018.1494643

Kolay, P.K., Puri, V.K., Lama Tamang, R., Regmi, G., and Kumar, S. (2019). “Effects of fly ash on liquefaction characteristics of Ottawa sand.” *International Journal of Geosynthetics and Ground Engineering*. https://doi.org/10.1007/s40891-019-0158-x

Lim, M.S., Wijeyesekera, D.C., Zainorabidin, A., and Bakar, I. (2012). “The effects of particle morphology (shape and sizes) characteristics on its engineering behaviour and sustainable engineering performance of sand.” *International Journal of Integrated Engineering*, **4**, 27-37.

Lo, S.R. and Wardani, S.P. (2002). “Strength and dilatancy of silt stabilized by a cement and fly ash mixtures.” *Canadian Geotechnical Journal*, **39**(1), 77-89. https://doi.org/10.1139/t01-062

Mahmoudi, Y., Cherif Taiba, A., Hazout, L., and Belkhatir, M., (2019). “Experimental evidence into the impact of sample reconstitution on the pore water pressure generation of Overconsolidated silty sand soils.” *Journal of Geo-Engineering*, **14**(4), 229-245. https://doi.org/10.6310/jog.201912_14(4).3

Mahmoudi, Y., Cherif Taiba, A., Belkhatir, M., Baille, W., and Wichtmann, T. (2020). “Characterization of mechanical behavior of binary granular assemblies through the equivalent void ratio and equivalent state parameter.” *European Journal of Environmental and Civil Engineering*. https://doi.org/10.1080/19648189.2020.1775708

Mahmoudi, Y., Cherif Taiba, A., Hazout, L., and Belkhatir, M. (2021). “Friction and maximum dilatancy angles of granular soils incorporating low plastic fines and depositional techniques effects.” *European Journal of Environmental and Civil Engineering*. https://doi.org/10.1080/19648189.2021.1999334

Mahmoudi, Y., Cherif Taiba, A., Hazout, L., and Belkhatir, M. (2022). “Comprehensive laboratory study on stress–strain of granular soils at constant global void ratio: Combined effects of fabrics and silt content.” *Arabian Journal of Geosciences*, **17**, 3269-3292. https://doi.org/10.1007/s11440-022-01480-1

Meyerhof, G.G. (1970). “Safety factors in soil mechanics.” *Canadian Geotechnical Journal*, **7**(4), 349-355. https://doi.org/10.1139/t70-047

Mogili, S., Mohammed, A.G., Mudavath, H., and Gonavaram, K.K. (2020). “Mechanical strength characteristics of fiber-reinforced pond ash for pavement application.” *Innovative Infrastructure Solutions*, **5**(70). https://doi.org/10.1007/s41062-020-00313-y

Monkul, M.M. and Yamamuro, J.A. (2011). “Influence of silt size and content on liquefaction behavior of sands.” *Canadian Geotechnical Journal*, **48**, 931-942. https://doi.org/10.1139/t11-001

Nawagamuwa, N. Wijesooriya (2018). “Use of fly ash to improve soil properties of drinking water treatement sludge.” *International Journal of Geoengineering*, **9**(3), 1-8. https://doi.org/10.1186/s40703-018-0071-5

NF P94-071-1 (1994). *Reconnaissance Et Essais—Essai De Cisaillement Rectiligne à la boîte - Partie 1: Cisaillement Direct*. AFNOR edition.

Phanikumar, B.R. and Nagaraju, T.V. (2018). “Effect of fly ash and rice husk ash on index and engineering properties of expansive clay.” *Geotechnical and Geological Engineering*. https://doi.org/10.1007/s10706-018-0544-5

Saeid, A., Amin, C., and Hamid, N. (2012). “Laboratory investigation on the compaction properties of lime and fly ash composite.” *International Conference on Civil and Architectural Applications (ICCAA’2012)*, Thailand, 79-83

Sadrekarimi, A. and Olson, S.M. (2012). “Effect of sample-preparation method on critical-state behavior of sands.” *Geotechnical Testing Journal*, **35**(4), 1-15. https://doi.org/10.1520/GTJ104317

Simatupang, M., Mangalla, L.K., Edwin, R.S., Putra, A.A., Azikin, M.T., Aswad, N.H., and Mustika, W. (2020). “The mechanical properties of fly-ash-stabilized sands.” *Geosciences*, **10**(4), 132. https://doi.org/10.3390/geosciences10040132

Sze, H.Y., A.M, F, and Yang, J. (2014). “Failure modes of sand in undrained cyclic loading: Impact of sample preparation.” *Journal of Geotechnical and Geoenvironmental*, **140**, 152-169. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000971

Wang, J.-J., Zhang, H.-P., Tang, S.-C., and Liang, Y. (2013). “Effects of particle size distribution on shear strength of accumulation soil.” *Journal of Geotechnical and Geoenvironmental*, ASCE, **139**(11), 1994-1997. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000931

Wang, Y., Shao, S., and Wang, Z. (2019). “Effect of particle breakage and shape on the mechanical behaviors of granular materials." *Advances in Civil Engineering*. https://doi.org/10.1155/2019/7248427

Xiao, Y., Long, L., Matthew Evans, T., Zhou, H., Liu, H., and Stuedlein, A.W. (2019). "Effect of particle shape on stress-dilatancy responses of medium-dense sands." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, **145**(2), 04018105. https://doi.org/10.1061/(ASCE)GT.19435606.0001994