Assessment of relative density on shear strength and volumetric characteristics of sand-EPS particulate mixtures

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Abstract

Geofoam is widely used in civil engineering projects due to its low unit weight, insensitivity to moisture variations and high erosion resistance. In present study, the effect of expanded polystyrene (EPS) particulates on the shear strength and volumetric characteristics of sand has been investigated using direct shear test. Sand has been mixed with 0.1, 0.2 and 0.3% EPS as dry weight of soil and compacted to relative densities (R_d) of 60, 65, 70, 75 and 80% in a shear box 60×60×26 mm and subjected to normal pressures of 100, 200 and 300 kPa. Results showed that by the addition of geofoam particulates to sand, shear strength characteristics such as cohesion, angle of internal friction and dilation as well as the stiffness of the mixtures decreased resulting in overall reduction of the shear strength. Increasing the relative density of sand-geofoam particulate mixtures, reversed the changes in the preceding characteristics. Shear strength and stiffness of samples improved with increase in normal pressure whereas dilation angles decreased. Cohesions displayed by samples are apparent and attributed to the penetration of sand particles into geofoam particulates resulting in particle confinement and thus reduction of dilation.

Keywords: Direct shear, Sand, Geofoam particulates, Relative density, Dilation.

1. Introduction

Expanded polystyrene (EPS) geofoam is a super-lightweight rigid cellular polymeric material with a density of about 1% of that of soil [1]. Geofoams are used as lightweight fillers to improve geotechnical characteristics and to reduce unit weight of soils [2, 3, 4, 5 & 6]. Lightweight materials are used as backfill of retaining structures to reduce lateral pressures, embankments to reduce driving forces, as seismic buffers to alleviate forces on retaining walls, in pavements to reduce noise, in pipeline trenches, etc. [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18 & 19]. Inclusion of lightweight material to cohesion-less soils increases damping ability to absorb dynamic stresses and reduce forces imposed on retaining walls, buried pipes, etc. [20, 21 & 22]. Researchers have investigated the effects of lightweight fill materials such as tire (rubber) and plastic strip wastes as well as EPS geofoam blocks on soil behavior.

Miki (1996) conducted direct shear tests to determine interface friction coefficient between geofoam-geofoam and geofoam-sand and reported coefficients ranging from 0.55 to 0.7 [23]. Horvath (1997) based on laboratory test results, divided stress-strain behavior of soil-geofoam mixtures into linear elastic, plastic with specified yield strength, linear and nonlinear hardening parts [1]. Negussey (1997) reported that friction at sand-geofoam interface is comparable to the angle of internal friction of sand alone [24]. Chrysikos et al. (2006) conducted direct shear tests to measure frictional resistance at the interface of geofoam blocks with densities of 15 and 30 kg/m^3 and materials such as concrete, soils, geomembranes, and geotextiles [25]. Liu et al. (2006) investigated the influence of polystyrene pre-puff beads/soil (PSPP/S) weight ratios and showed unit weights to vary between 7 to 11 kN/m^3 [26].

Abdelrahman et al. (2008) reported that increase in the normal stress and decrease in geofoam density cause an increase in both the peak and residual friction coefficients of EPS blocks [27]. Kim et al. (2008) showed that inclusion of EPS particulates results in reducing the unit weights to 6 to 15 kN/m^3 [28]. Deng and Xiao (2010) studied the stress-strain behavior of EPS particulate-sand mixtures and showed decrease in strength with increasing EPS content with mixtures being 26 to 63% lighter than earth fill materials [29]. Heydarian et al. (2012) reported that the addition of geofoam particulates to sandy soils resulted in decrease of internal friction angle and increase of apparent adhesion and increased uniaxial compressive in clayey soils [30]. Rocco and Luna (2013) investigated the undrained shear strength of clay-EPS mixtures in saturated and unsaturated conditions. Results indicated that undrained shear strengths of saturated mixtures were unaffected whereas for partially saturated mixtures, EPS content caused significant reduction [31].

Padade and Mandal (2014) by blending fly ash with EPS particulates and cement and reported that the compressive strength of expanded polystyrene-particulates geomaterial increases considerably if cement-to-fly ash ratios of 10, 15 and 20% were used. Compared with EPS block geofoam, EPS particulates mixed geo-material showed higher density, compressive strength and stiffness which is suitable as fill material [32]. Effects of EPS particulates gradation on the stress-strain behavior of EPS-sand mixtures was investigated by Edinçliler and Özer (2014). Results showed that deviatoric stress of EPS-sand mixture is a function of EPS particulate content and size distribution [33].

Padade and Mandal (2014) investigated the interaction between geofoam-geofoam, geofoam-geotextile and geofoam-geogrid using EPS blocks 0.15, 0.2, 0.22 and 0.3 kN/m^3 in density and reported that shear strengths at interface is not significantly influenced by density of geofoam [34]. Özer and Akay (2016) by conducting direct shear tests on EPS blocks reported that shear strength is mainly dependent on its cohesion while interface shear strength is dependent on both adhesion and friction coefficient [35]. Direct shear tests were also conducted on geofoam-sand interface by AbdelSalam and Azzam (2016) and no significant change in interface friction coefficient especially under low normal stress was observed in both dry and wet conditions [36]. Khan and Meguid (2018) showed that geofoam-sand interface developed frictional resistance that is much larger than measured for geofoam-PVC interface [37].

Dynamic properties of sand-EPS particulate mixtures were evaluated using resonant column and cyclic triaxial tests at small and large strains by El-Sherbiny et al. (2018). Results indicated a decrease in shear stiffness with increasing EPS content at all strain levels. Material damping was relatively unaffected at small and increased at larger strains [38]. Alaie and Jamshidi Chenari (2018) also conducted investigated dynamic properties of EPS-sand mixtures and reported damping of EPS-sand mixtures to increase with increasing EPS content [39]. In a later study Alaie and Jamshidi Chenari (2019,2020) by conducting cyclic triaxial tests on EPS-sand mixtures showed that shear velocity and modulus decrease with increasing EPS content and damping ratio decreases during the initial loading cycles and levels off afterwards [40,41]. Nawghare and Mandal (2020) and Ali et al. (2023) studied fly ash - EPS mixtures and reported that smaller EPS particulates proved more effective on improving shear strength than larger EPS particulates [42 & 43]. Abbasimaedeh et al. (2021) studied behavior of uncemented EPS -clayey soil mixtures as lightweight fill and reported that EPS beads caused substantial mechanical failure in direct shear with drastic decay of CBR and compressibility parameters [44]. Alaie et al. (2021) studying EPS-sand mixtures using laminar box on shaking table showed that deformations under dynamic loading were reduced and that the damping ratio and shear modulus depend on the EPS bed content [45].

Zhu et al. (2022) conducted dynamic triaxial tests on sand-EPS (LSES) mixtures and control sand (CS) and stated that dynamic strength of LSES decreased with the increase in EPS particulates content due to the low strength and smooth surfaces of EPS particulates [46]. Ge et al. (2022) investigated the shear performance of the sand-EPS mixtures at different moisture contents. Results showed that with increase in moisture content, the shear strength and the internal friction angle of sand-EPS mixtures initially decreased and then increased whereas cohesion increased first and then decreased [47]. Jili et al. (2022) explored the resistance characteristics of Shanghai clay-EPS mixtures and showed that with increase in EPS particle size, the compressive strength, compression and rebound index together with ductility of mixtures increased [48].

Bekranbehesht et al. (2023) investigated the influence of EPS beads on the shear stiffness of quartz and calcareous based materials using bender element tests and reported that maximum shear modulus increases with confining pressure and decreases with increasing void ratio and EPS content [49]. Tao et al. (2023) evaluating the dynamic modulus and damping characteristics of modified expanded polystyrene lightweight soil and reported that EPS content plays a decisive role on elastic modulus and damping ratio of the mixture [50]. Karimpour-Fard et al. (2023) evaluating compressibility of EPS beads and EPS-sand mixtures using triaxial tests, reported better agreement between CD and CU stress paths when EPS compressibility is considered [51]. Demiröz & Diker (2023) investigating the geotechnical properties of fill-EPS-waste tire observed that strength increased with increase in cement ratio, and decreased with EPS ratio and waste tires were found to have no impact on strength [52]. Karademir (2023) investigated soil type and loading condition effects on soil-geofoam interactions and reported that peak and residual shear stresses increased with increase in normal stress and granular compared with cohesive soil demonstrated larger frictional strengths and the higher the granular soil angularity, the larger the interface shear strength [53].

Considering previous investigations, it is seen that effects of relative density as an influential factor on sand-EPS particulate mixtures has not formerly been assessed. Thus, in current research the influence of this factor on shear strength parameters, stress-strain and volumetric characteristics of sand-EPS particulate mixtures has been investigated. For this purpose, sand has been mixed with 0.1, 0.2 and 0.3% EPS particulates as dry weight of soil and compacted to 60, 65, 70, 75 and 80% of the sand maximum dry density. Samples 60×60×26 mm was prepared in slightly moist condition and tested using direct shear test with normal pressures of 100, 200 and 300 kPa.

2. Experimental study

2.1. Materials

2.1.1. Sand

Due to suitable drainage characteristics and insensitivity to moisture variations, granular soils are mostly used as fill behind retaining walls [54, 55, 56, 57, 58, 59, 60 & 61]. Thus, in current research to be in accord with previous investigators a sandy soil has been selected for the investigations. The sand used was collected from Shahriar mines west of Tehran which are the main source of sand for civil engineering projects. Summary of the sand characteristics are presented in Table 1 with its maximum and minimum dry unit weights and the particle size distribution determined according to ASTM D4253 (2016), ASTM D4254 (2016) and ASTM D6913 (2017) respectively [62, 63 & 64]. Considering Figure 1, it is observed that the soil comprises of 99% sand particle. According to Unified Soil Classification System (USCS) sand is grouped as SP (poorly graded sand) [65].

2.1.2. EPS particulates

The EPS particulates used was obtained from a regional supplier of EPS materials for engineering, manufacturing, and packaging industries. EPS particulates are used to produce geofoam blocks 2000×500×250 mm with a density of 12 kg/m^3 with particulates varying in size from 2 to 5 mm. EPS particulates used is portrayed in Figure 2 with the physical and mechanical properties shown in Table 2 [66].

2.2. Apparatus

Direct shear test is the simplest method used for determination of granular soil shear strength characteristics as depicted in Figure 3. In current research, direct shear tests were conducted in accordance with the specifications outlined by ASTM D3080 [67]. Shear box 60×60×26 mm was adopted for the preparation of the samples and shear load was applied at a rate of 1 mm/min. During tests, horizontal and vertical displacements were measured employing LVDTs, and a load cell together with an automatic data recording system to measure and record shear force and displacements. Shear stresses presented have been calculated implementing modified shear surface areas.

2.3. Sample preparation

Samples were prepared by mixing sand with 0.1, 0.2 and 0.3% EPS particulates as dry weight of soil. Constituents were slightly moistened (<3%) to facilitate mixing and prevent segregation of EPS particulates.

Moistening helped EPS particulates to be more uniformly distributed in the mixture. Mass based proportions of sand and EPS particulates for different compositions and relative densities were determined and are presented in Table 3. Constituents were thoroughly mixed using an electric mixer until a homogeneous mixture was achieved. Samples were prepared and compacted on a separate table and subsequently transferred to the direct shear test apparatus. Samples were compacted to relative densities of 60, 65, 70, 75 and 80% (Fig. 4 (a)) and to be in accord with previous researchers subjected to normal pressures of 100, 200 and 300 kN/m^2. These relative densities were adopted so the behavior of the sand-EPS mixtures could be assessed over a wide range of compaction degrees from medium to dense. Due to heterogeneity all tests were repeated 3 times.

To determine shear strength parameters of the geofoam, a series of direct shear tests were conducted on geofoam cubic specimens 60×60×26 mm as shown in Fig. 4 (b). The samples were subjected to the same normal pressures as soil-EPS particulate mixtures and the results were used to help interpret the shear stress-shear displacement and volumetric characteristics of the composite mixtures.

3. Results and discussions

3.1. Expanded polystyrene samples (EPS)

To determine shear strength characteristics of the expanded polystyrene, 9 direct shear tests were conducted on cubic samples cut out of EPS blocks (i.e. geofoams). As the results obtained were very close, variations of shear stress-horizontal displacements for only a set of three samples are presented as representative in Fig. 5. It is observed that shear stresses continuously increase up to the maximum horizontal displacement of 7 mm which is equivalent to approximately 12% strain with no distinct failure points. The rate of variations in shear stresses with horizontal displacement show two distinct phases. During the first phase which starts from the beginning to a horizontal displacement of 1 mm (1-2% strain), the rate of increase in shear stresses is relatively high and thereafter the second phase starts exhibiting lower rate of increase in shear stresses. Due to the compressible nature of the EPS block, even after 12% strain the trend of changes show that the sample is being constantly compressed and becomes slightly stronger. Results show that even EPS samples subjected to higher normal pressures display greater shear stresses at a particular horizontal displacement. Effects of normal pressure at early stages of the tests are marginal and become intensified at greater horizontal displacements because the sample becomes compressed and consequently stronger. None of the EPS block samples tested reached a distinct maximum or ultimate shear stress.

The formation of two distinct phases in the shear stress-horizontal displacement diagram for the EPS block has also been reported by other researchers. The boundary between the two phases have been reported to form at 1 to 4% strain depending on the density and dimensions of the geofoam, applied normal stress and the rate of loading [35, 37, 68]. This phenomenon is probably due to the fact that EPS particulates forming the geofoam block that are in contact with shear box walls become deformed and strained more than inner parts of the EPS block because of stress concentration. Hence, the deformed parts cannot fully contribute to increase in shear strength.

Figure 6 shows the relationship between maximum shear stress values reached at 7 mm displacement versus normal pressure for the 9 samples tested. Three failure envelopes have overlapped with the summary of the shear strength parameters presented in Table 4. Results clearly show that for the EPS blocks apparent cohesion is the predominant parameter with an average value of 18 kPa with friction having very little influence on shear strength. The angles of internal friction determined have very low values of approximately 3°.

Summary of the direct shear tests conducted on EPS blocks by some other researchers are presented in Table 5. It observed that the shear strength parameters are influenced by factors such as normal stress, density and dimensions of EPS block. The smaller friction angle and the cohesion attained for EPS in current study is attributed to the lower density and the relatively larger normal stresses applied.

3.2. Sand samples

To determine sand's shear strength characteristics, a number of direct shear tests were performed on samples prepared at 60, 65, 70, 75, 80 and 100% relative densities. Figures 7 (a) to (f) show variations of shear stress-horizontal displacement for the above-mentioned specimens subjected to normal pressures of 100, 200 and 300 kPa. It is observed that at the low relative densities of 60 and 65%, shear stresses increase gradually with horizontal displacements and samples do not display distinct maximum or ultimate states. By increasing the relative densities to particularly 80 and 100%, shear stresses increase very rapidly with horizontal displacements and samples clearly show maximum and ultimate states which have overlapped. The rapid rates of increase in shear stresses signify stiffness and thus the higher the normal pressure, the greater the subsequent improvement in shear strengths. These changes in behavior are due to the greater confinements provided at higher normal pressures which restrict particle displacement and thus improve intergranular interactions [70, 71, 72, 73 & 74]. The differences in confinements and intergranular contact points in loose and dense sand is schematically shown in Fig. 8.

Figures 9 (a) to (f) portray vertical versus horizontal displacements for the sand samples having different relative densities. All samples show dilative behavior during shearing the amount of which substantially increases with the increase in density. The least and the most dilative changes have been displayed respectively by samples with R_d=60 and 100%. In samples with the lowest relative density of 60%, because of least intergranular interactions and the highest void ratio, particles do not effectively interact and easily slide past each other resulting in the lowest shear strength. In contrast in samples of higher relative densities, due to the presence of greater number of particles and lower void ratio in a constant volume, intergranular contacts significantly increase and grains cannot easily slide relative to each other during shearing and have to initially lift over adjacent particles and then displace. The lifting and the dislodgement of the soil grains result in increased void ratio and thus dilation. The amount of dilation reduces by increase in normal pressure which is attributed to probable particle breakage and the reduction in particle size. Also, the dilative behavior creates an uplift force, which is counteracted by the normal pressure which reduces the amount of dilation (see Fig. 10). Thus, the greater the normal pressure, the smaller the amount of dilation also confirmed by other researchers [75, 76, 77 & 78].

Failure envelopes for specimens with different relative densities are depicted in Figure 11, with summary of results presented in Table 6. Results are the average of two tests conducted on each particular sample which have been rounded to the nearest whole number. It is observed that by increasing the relative densities from 60 to 100%, angles of internal friction have improved from 37 to 49 degrees and the apparent cohesions from 0 to 16 kPa representing enhancement in shear strength parameters of 32 and 160% respectively. It is worth mentioning that the apparent cohesions are attributed to inherent nature of direct shear apparatus and are small and thus can be neglected in designs.

3.3. Sand-EPS particulate mixtures

In the third stage of the investigation, direct shear tests were conducted on sand-EPS particulate mixtures. Sand was mixed with 0.1, 0.2 and 0.3% EPS particulates as dry weight of soil and compacted at relative densities of 60, 65, 70, 75, 80 and 100%. To reduce the volume of the article, only the results of sand-EPS particulate mixtures with 80% relative density have been presented in Figure 12. Results of equivalent sand samples without EPS particulates have also been included for comparative purposes. Results show that for samples subjected to a specific normal pressure, the inclusion of EPS particulates reduces shear stresses particularly with increase in normal pressure. Generally, samples containing higher percentage of EPS particulates, give lower shear stresses corresponding to a particular horizontal displacement and normal pressure. By the addition of EPS particulates of very low rigidity compared to sand particles, intergranular interactions and thus friction at interfaces is reduced leading to overall reduction of shear strength. EPS particulates have low density and high compressibility compared to soil particles. So, increasing the amount of EPS particulates in a constant volume, leads to the reduction of soil intergranular surfaces and thus overall reduction of shear strength. Results also show that with increase in normal pressure, the reduction in shear strength of the sand-EPS mixture increases. The increase in normal pressure causes compression of the highly compressible EPS particulates and thus reduces their interaction with sand grains leading to overall reduction in mixture shear strength. With increase in EPS content, not only sand-EPS particulate contact surfaces increase but also the probability of EPS-EPS particulate surfaces increases. These changes result in the reduction of sand-sand friction at interfaces which mainly contribute to shear strength clearly seen from the results depicted in Fig. 12.

Considering the behavior of sand-EPS particulate mixtures, the shear strengths attained could be the consequence of i) sand-sand, ii) sand-EPS, and iii) EPS-EPS interactions at contact surfaces also reported by Deng and Xiao, 2010 [29]. As sand particles have higher rigidity and strength in comparison with the EPS particulates, it would be logical to claim that their interactions (i.e. mechanism (i)) is the main contributor to the mixture shear strength and mechanisms (ii) and (iii) are less influential. Figure 12 clearly shows that regardless of the applied normal pressure, addition of EPS particulates to sand reduces the shear strength.

Figure 13 displays vertical versus horizontal displacements for sand-EPS particulate mixtures with R_d=80% subjected to σ_n=100, 200 and 300 kPa. It is seen that all specimens show dilative behavior during shearing similar to sand samples. The amount of dilation demonstrates reduction with increase in normal pressures and EPS percentage. In specimen containing higher percentage of EPS particulates and exposed to greater normal pressures, soil grains penetrate the EPS particles preventing particle dislodgement and vertical displacement and subsequent rotation as a result of intergranular failure leading to overall reduction in dilation. At the same time greater normal pressures result in higher compression of the EPS particulates and thus further volume reduction. All sand-EPS mixtures subjected to different normal pressures show smaller dilation at a particular horizontal displacement than sand samples clearly showing that EPS particulates restrict soil particle displacements.

The amount of dilation for sand and sand-EPS mixtures reduces with increase in normal pressure which is probably the result of some particle breakage at contact points in sand samples and the compression of the EPS particulates in sand-EPS mixtures. Probable sand-EPS interactions are schematically shown in Figure 14. As seen, with increase in EPS percentage, more sand particles can penetrate into EPS particulates. Therefore, the amount of the uplift force as well as the dilation of the sand-EPS mixture is further reduced. As mentioned earlier, normal pressure counteracts the uplift force, reducing its effect and the amount of dilation for reinforced and unreinforced sand. Different effects of higher compared to lower normal pressures on sand-EPS mixtures is that it allows sand particles to penetrate more into the EPS particulates both before and during shearing. In other words, higher normal pressure causes greater compression of the EPS particulates, which further reduces the dilation of the sand-EPS mixture.

Figure 15 demonstrates the relationship between maximum shear strengths and EPS content for mixtures with R_d=80%. It is observed that by the addition and increase in EPS content, maximum shear strengths reduce at all normal pressures examined and the rate of reduction increases with increase in the magnitude of normal pressure. Although EPS inclusion reduces maximum shear strengths, but it also reduces density of the soil-EPS mixture rendering it suitable for possible use as backfill for reduction of lateral pressure on earth retaining structures and save costs.

Variations of dilation angles with normal pressure for sand-EPS mixtures are shown in Figure 16. Results show that with increase in the magnitude of normal pressures as well as EPS content, dilation angles reduce. The relationship is approximately linear with the greatest rate of reduction displayed by sand-0.3% EPS particulate samples.

The influence of EPS particulates on shear strength parameters of the mixtures prepared with different densities are shown in Figures 17 and 18. Results show that in general by inclusion of EPS particulates, angle of internal friction reduces whereas apparent cohesions increase and at a particular EPS content, by increase in relative density, angles of internal friction are improved. This is caused by increase in the number of sand grains in the mixture promoting greater sand-sand intergranular interactions (i.e. mechanism (i)) as well as reduction in soil porosity resulting in higher friction and thus shear strengths. Presence of EPS particulates in mixtures reduce sand intergranular interactions resulting in the reduction of internal friction and thus shear strengths. In sand-0.1% EPS mixtures the angle of friction has increased by 10° whereas in sand-0.3% EPS specimens φ has increased by approximately 8 degrees by increase in relative density from 60 to 80%. These changes distinctly show that at higher EPS contents, greater numbers of EPS particulates present result in the reduction of grain-grain interaction and subsequently the overall shear strength (Fig. 18).

Considering Figure 18, it is seen that by increase in relative density and subsequent reduction in void ratio, apparent cohesions in both sand and sand-EPS mixtures increase. Apparent cohesions in the sand samples may be attributed to the suction caused by the addition of small amount of water used for moistening the mixtures as well as the internal mechanism of the direct shear apparatus. In accord with other researchers, it is suggested to neglect the low cohesion values [79 and 80]. For sand-EPS mixtures, as sand grains penetrate EPS particulates, their interaction using Mohr-Columb failure criteria appears as apparent cohesion also reported by Shirazi et al. (2018) [81]. With increase in relative density, the number of sand particles penetrating the EPS particulates increase, resulting in higher apparent cohesions.

By increasing relative density of mixtures, the shear strengths and therefore bearing capacity is improved. As a result of compaction for achieving the desired densities, sand grains and EPS particulates become tightly compressed and consequently void ratio reduces resulting in greater and more effective interactions at interfaces. Improved interactions increase stiffness and therefore shear strength of the mixtures. According to the results shown on Figure 19, the highest shear strength of 320 kPa was achieved by sand+0.1% EPS mixture with R_d=80% subjected to σ_n=300 kPa and the lowest shear strength of 75.4 kPa was attained by samples of sand+0.2%EPS particulates with R_d=60% at σ_n=100 kPa. Reduction in shear strength of samples with the highest relative density of 80% and 0.3% EPS particulate subjected to normal pressures of 300 kPa is greater than the specimens with lowest relative density of 60% subjected to σ_n=100 kPa. This is attributed to the greater number of EPS particulates in a constant volume resulting in the reduction of sand intergranular interactions.

Dense granular materials tend to dilate whereas loose granular materials show compression during shearing. Dilation angle (Ψ) is determined by the equation 1 using the values of vertical and horizontal displacements that represent maximum slope of the vertical versus horizontal displacement curves.

$$\tan(\Psi) = \frac{dv}{dh}$$

(1)

Figure 20 presents the effects of EPS content and normal pressure on dilation angles at different relative densities. The highest dilation angle of 20.7° was achieved by the sand+0.1% EPS mixture with relative density of 80% and subjected to normal pressure of 100 kPa. By increasing relative density, vertical stress and EPS content in mixtures, dilatation angles decrease due to compressibility of EPS particles and thus overall reduction in volume changes.

4. Conclusions

The use of lightweight backfills behind earth retaining structures can significantly reduce lateral pressures or alleviate seismic forces. One of the methods is to use EPS blocks behind retaining structures which in irregular conditions is rather difficult and thus can be replaced by EPS particulates which can easily be mixed with soil in just the same manner as chemical admixtures. In current study the effects of EPS particulates on shear strength characteristics of sand with different relative densities and subjected to various normal pressures has been investigated and the following conclusions reached:

- Increasing the relative density, significantly improves shear strength characteristics of sand and by the inclusion of EPS particulates, shear strength characteristics of the mixtures are reduced. EPS particulate addition to sand reduces the angle of internal friction and increases apparent cohesion of mixtures.
- The addition of EPS particulates reduces the dry unit weight of mixtures which have the potential to be used as light weight backfill in geotechnical engineering projects. Due to the high compressible potential of the EPS particulates, increasing normal pressure significantly reduces dilation of mixtures. The higher the normal pressure, the lower the dilation of mixture.
- By increasing the relative density of the samples, the shear strength characteristics of mixtures increase due to the decrease in porosity and the more effective intergranular interactions. Also, as the relative density of mixtures increase, the amount of dilation and the dilation angles increase. By increasing the relative density, mixtures become and behave more rigidly and reach failure state at lower shear displacements.
- By increasing the relative densities from 60 to 100%, angles of internal friction improved from 37 to 49 degrees and the apparent cohesions from 0 to 16 kPa which represent enhancement in shear strength parameters of 32 and 160% respectively.
- According to the important results of this study, the inclusion of EPS particulates in sand does not result in a significant reduction in shear strength. Therefore, EPS can be used in various construction projects as blocks or particulates in combination with soil. It can be used for railways, slope stability, backfill in retaining structures, and fill in embankments.

5. Data Availability Statement

All data, models or code that support the findings of the current study are available from the corresponding author upon reasonable request.

6. Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures captions:

Figure 1. Sand particle size distribution curve.

Figure 2. EPS particulates.

Figure 3. Schematic of direct shear test apparatus.

Figure 4. Illustration of samples prepared for direct shear testing: a) sand-EPS particulate mixture and b) EPS block.

Figure 5. Shear stress-horizontal displacement of EPS block.

Figure 6. Failure envelopes for EPS blocks.

Figure 7. Shear stress-horizontal displacement of sand at: a) 60%, b) 65%, c) 70%, d) 75%, e) 80% and f) 100% relative densities.

Figure 8. Comparison of intergranular points and confinements in direct shear test: a) idealized loose and b) dense sand.

Figure 9. Vertical versus horizontal displacements of sands at: a) 60%, b) 65%, c) 70%, d) 75%, e) 80% and f) 100% relative densities.

Figure 10. Interaction of normal pressure and uplift forces on sand grains during shearing.

Figure 11. Failure envelopes for sands with different relative densities.

Figure 12. Shear stress-horizontal displacement of sand-EPS particulate mixtures with R_d=80%; a) σ_n=100 kPa, b) σ_n=200 kPa, c) σ_n=300 kPa.

Figure 13. Vertical-Horizontal Displacement of sand-EPS mixtures with R_d=80%; a) σ_n=100 kPa, b) σ_n=200 kPa, c) σ_n=300 kPa.

Figure 14. Position of sand and EPS particles before and after shearing.

Figure 15. Variations of maximum shear strength-EPS content in mixtures with R_d=80%.

Figure 16. Dilation angle-normal pressure for sand-EPS mixtures with R_d=80%.

Figure 17. Friction angle-EPS content in mixtures with different relative densities.

Figure 18. Apparent cohesion-EPS content in mixtures with different relative densities.

Figure 19. Shear Strength-EPS content of all mixtures.

Figure 20. Variations of dilation angles for sand-EPS mixtures of different densities subjected to σ_n=100, 200 and 300 kPa.

Tables' captions:

Table 1. Sand characteristics

Table 2. Physical and mechanical properties of EPS particulates

Table 3. Sand-EPS particulate mixtures investigated

Table 4. Shear strength parameter for EPS blocks

Table 5. Summary of direct shear test conducted on EPS blocks

Table 6. Summary of sand shear strength parameters at different relative densities

Figures:

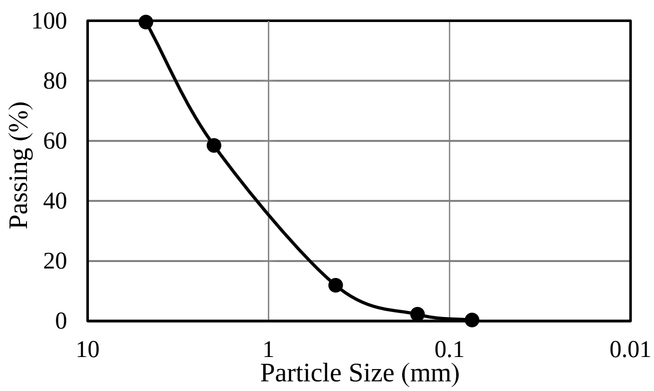

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Figure 2. EPS particulates.

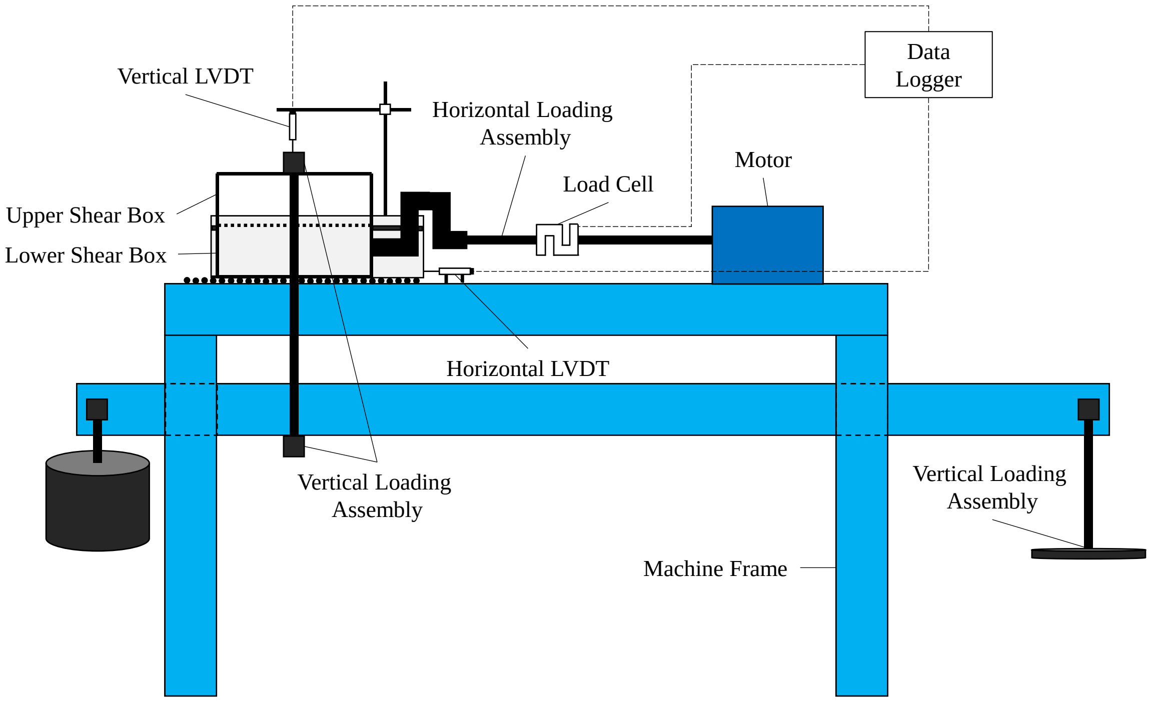


Figure 3. Schematic of direct shear test apparatus.

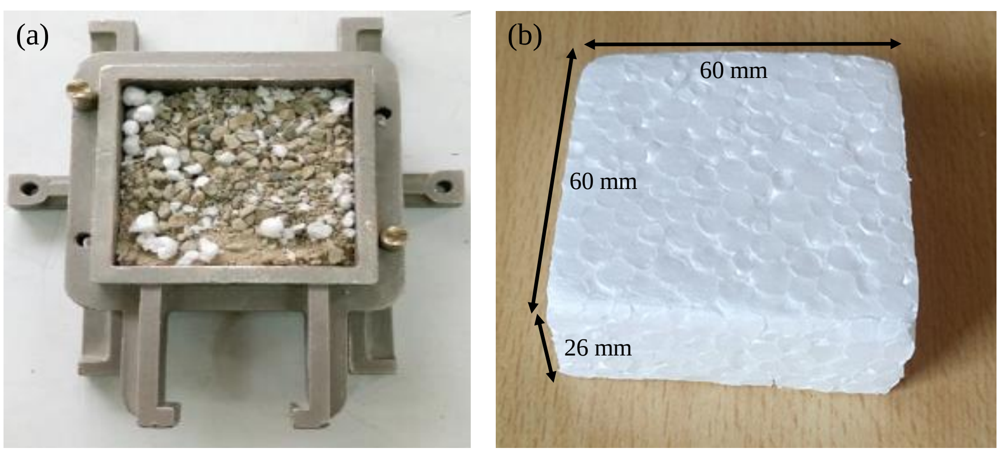


Figure 4. Illustration of samples prepared for direct shear testing: a) sand-EPS particulate mixture and b) EPS block.

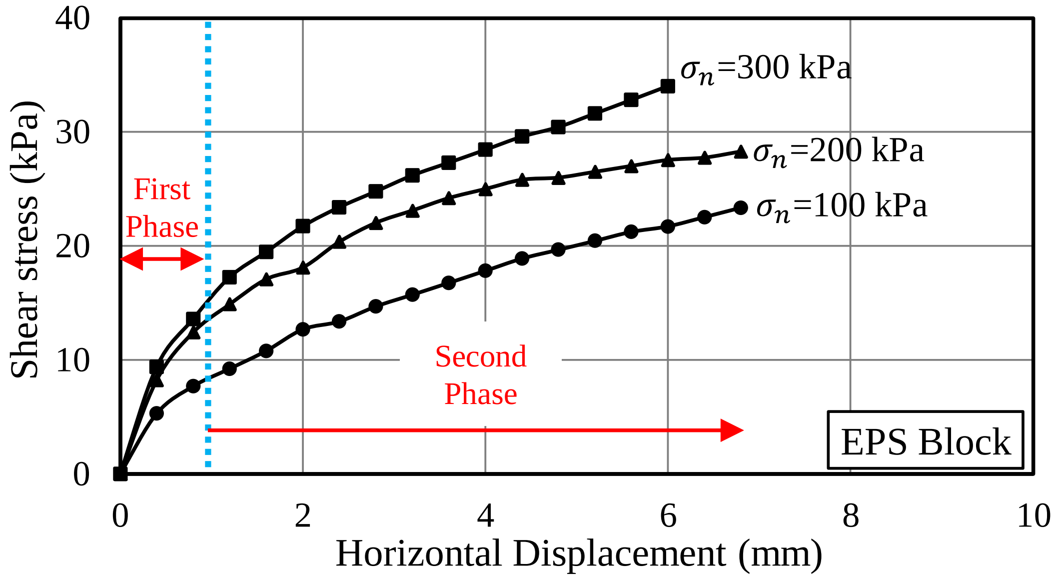


Figure 5. Shear stress-horizontal displacement of EPS block.

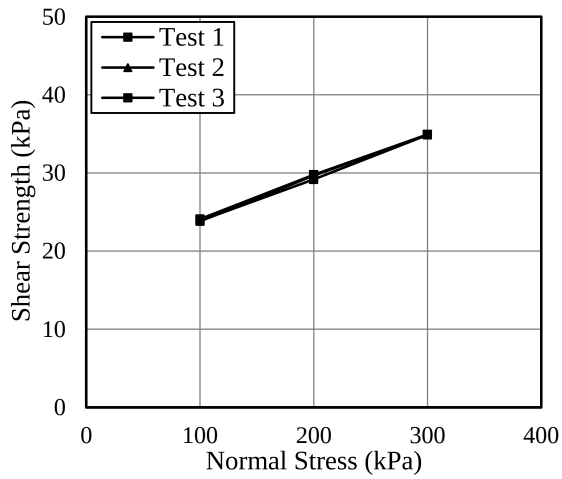
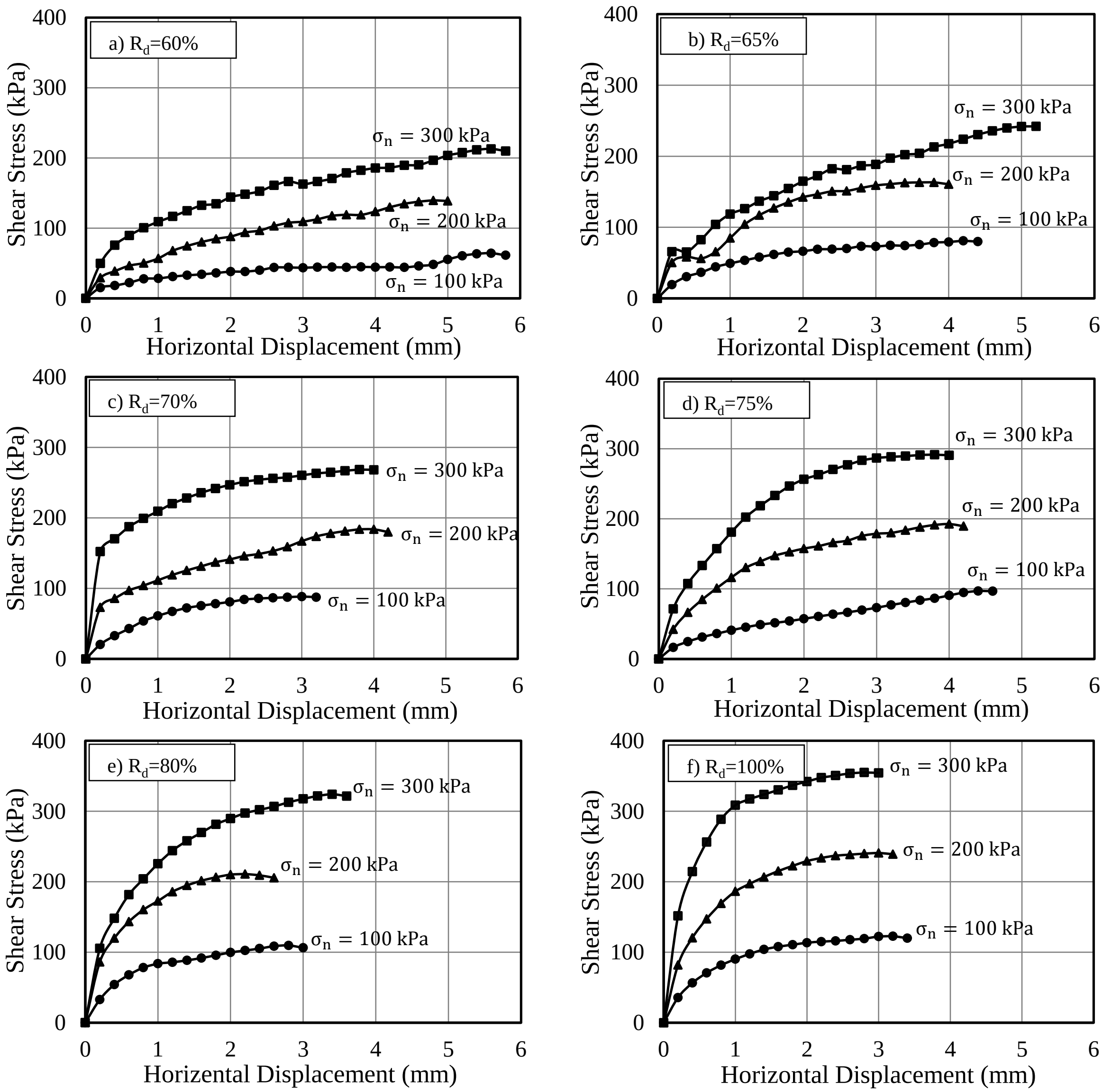


Figure 6. Failure envelopes for EPS blocks.



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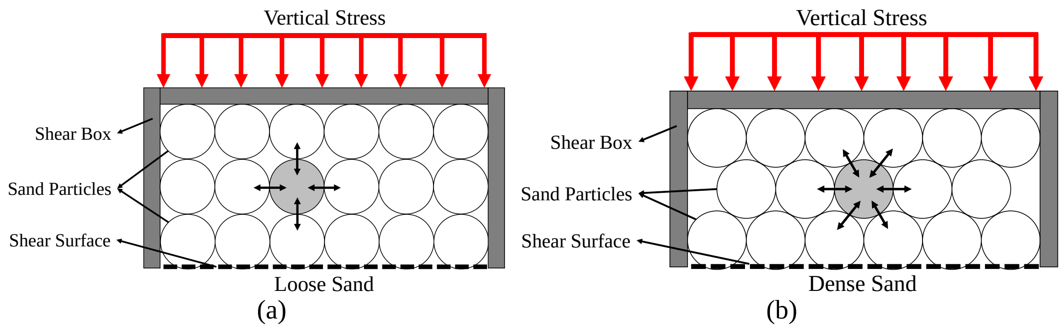

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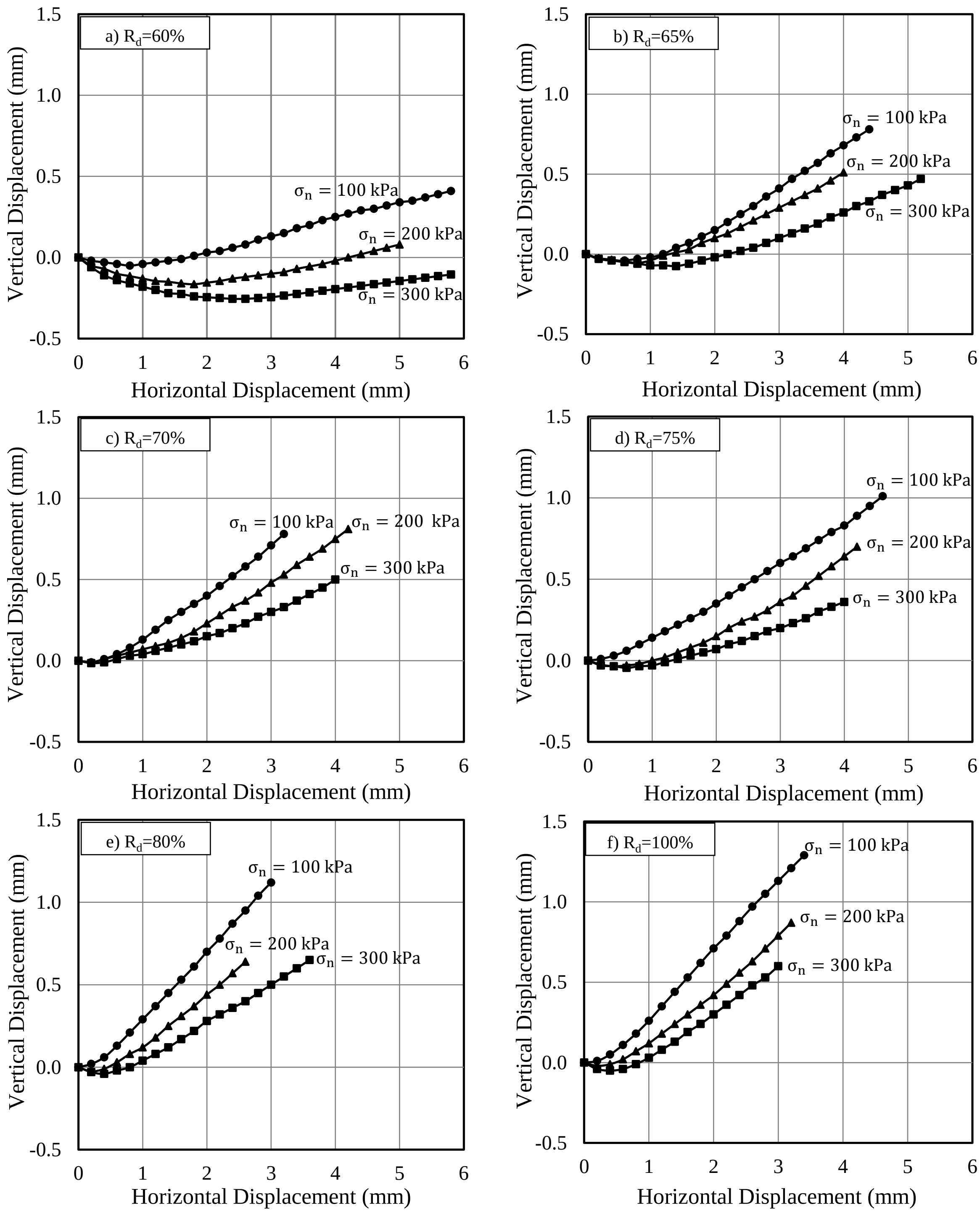

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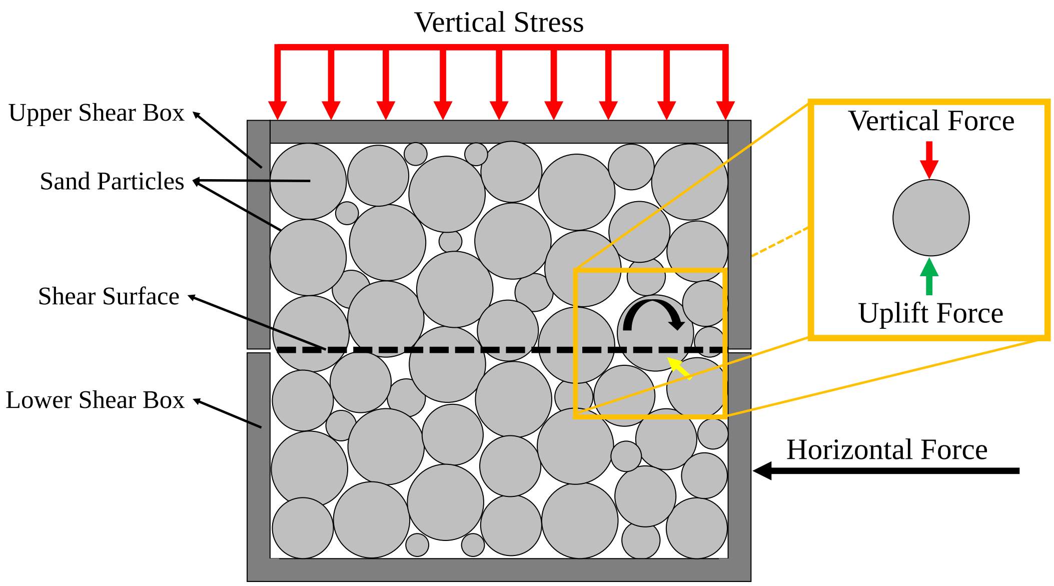

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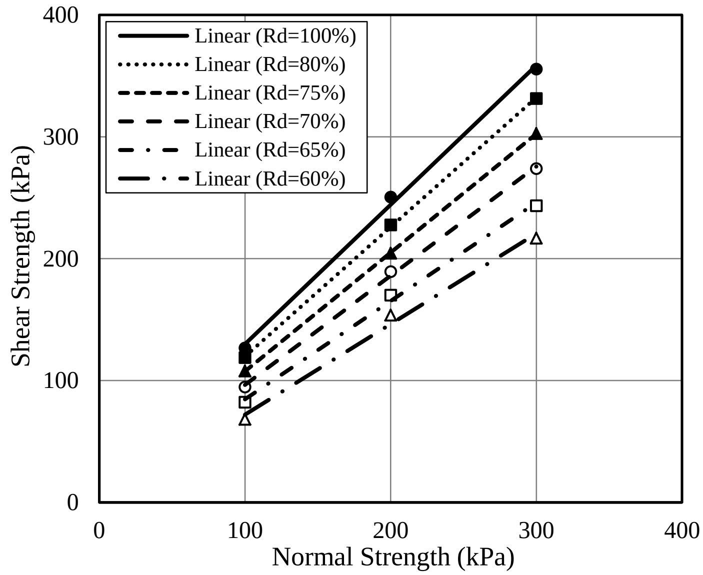

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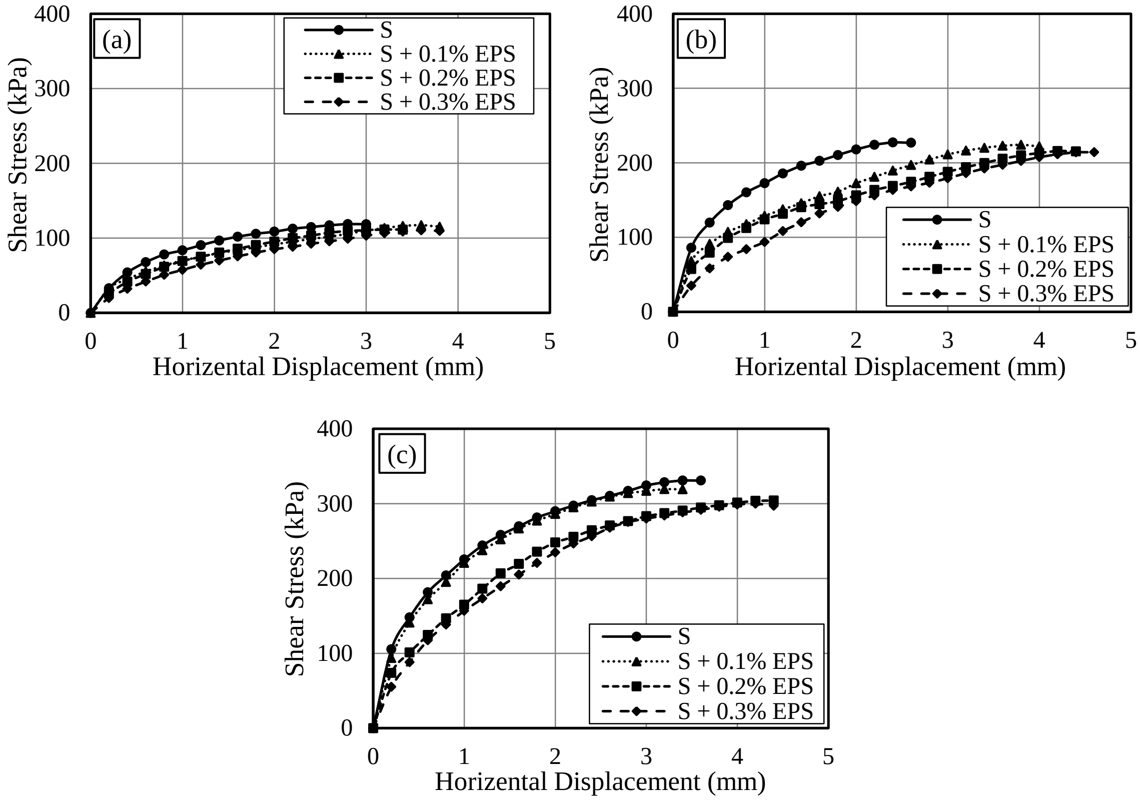

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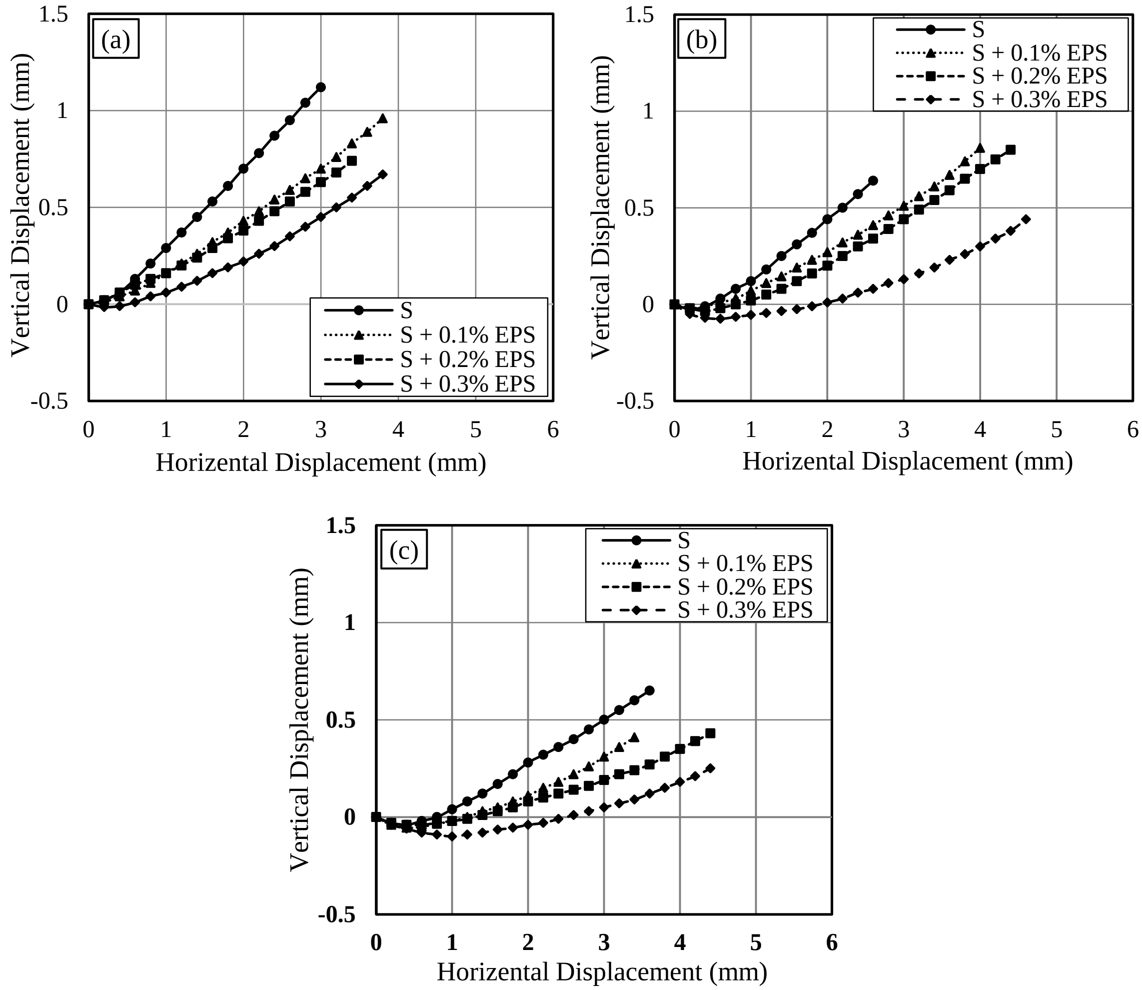

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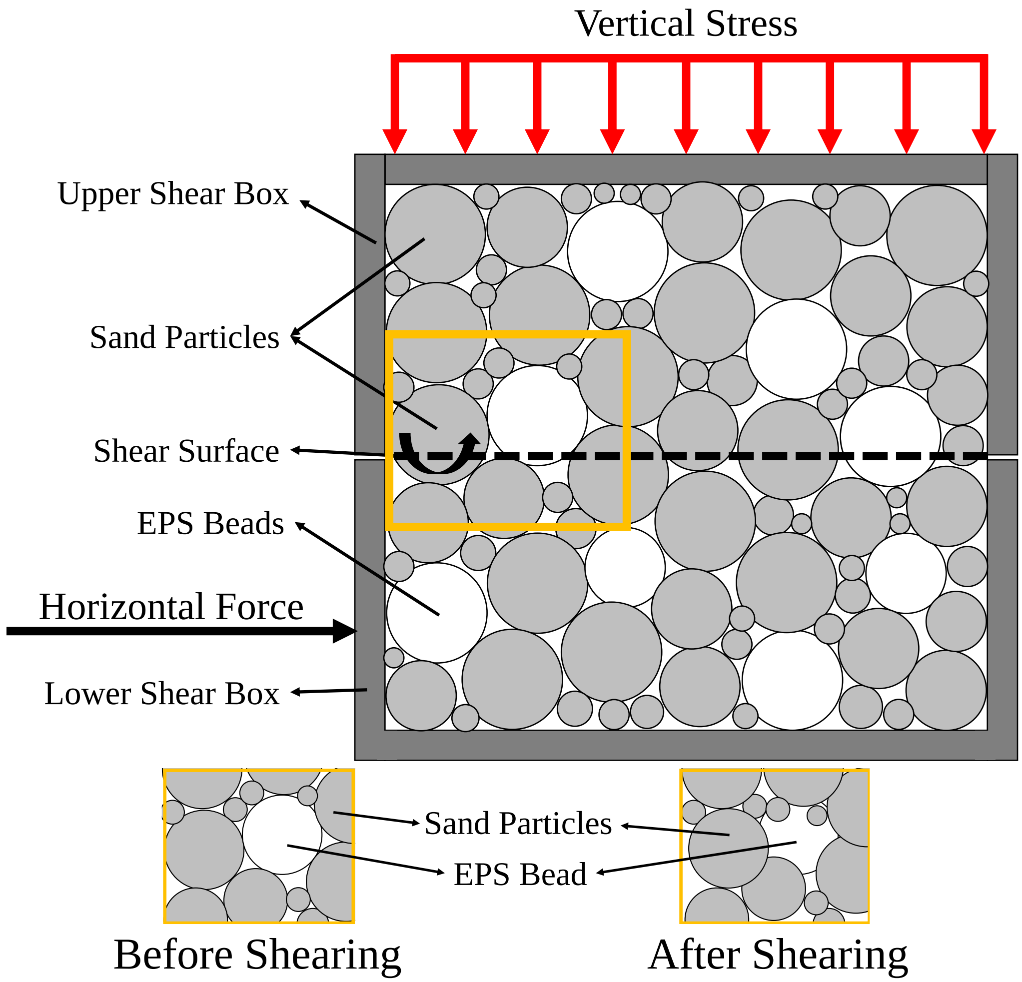

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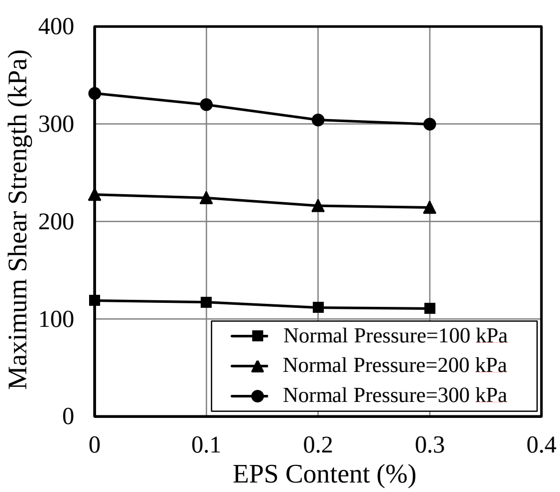

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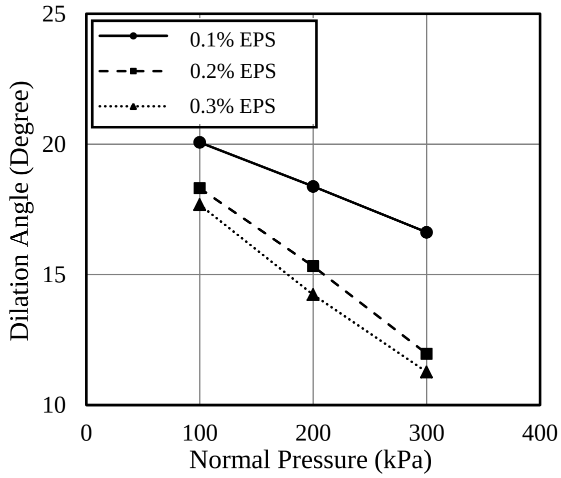

Figure 16. Dilation angle-normal pressure for sand-EPS mixtures with R_d=80%.

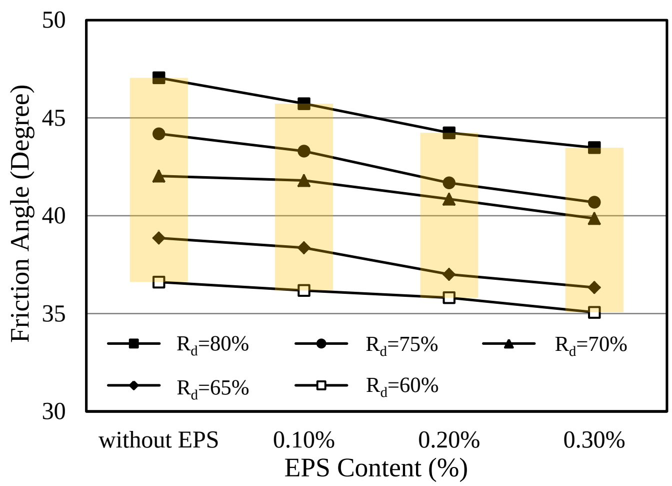

Figure 17. Friction angle-EPS content in mixtures with different relative densities.

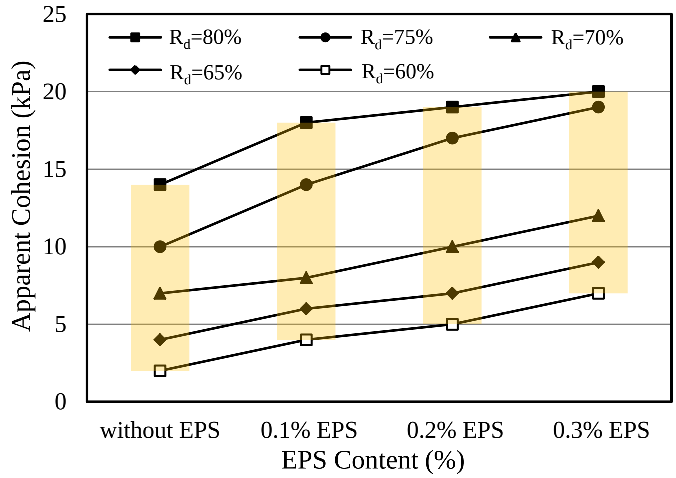

Figure 18. Apparent cohesion-EPS content in mixtures with different relative densities.

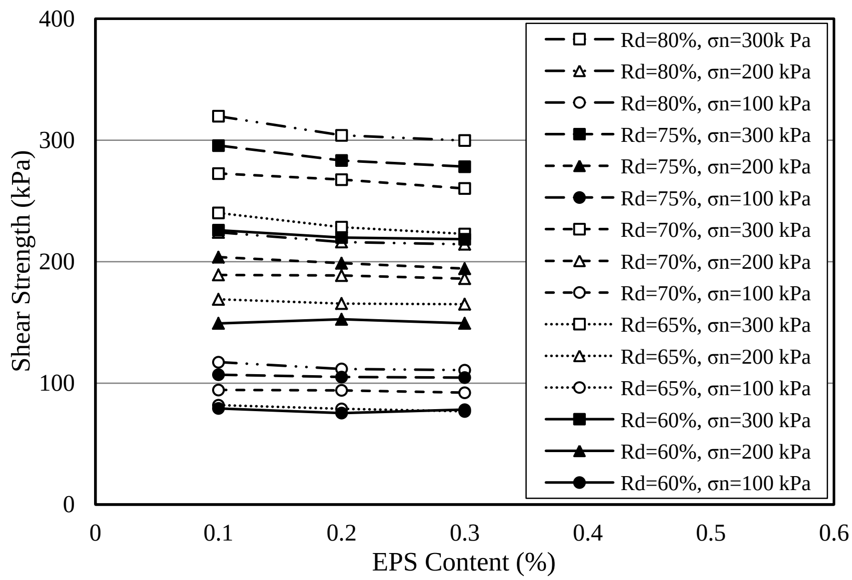

Figure 19. Shear Strength-EPS content of all mixtures.

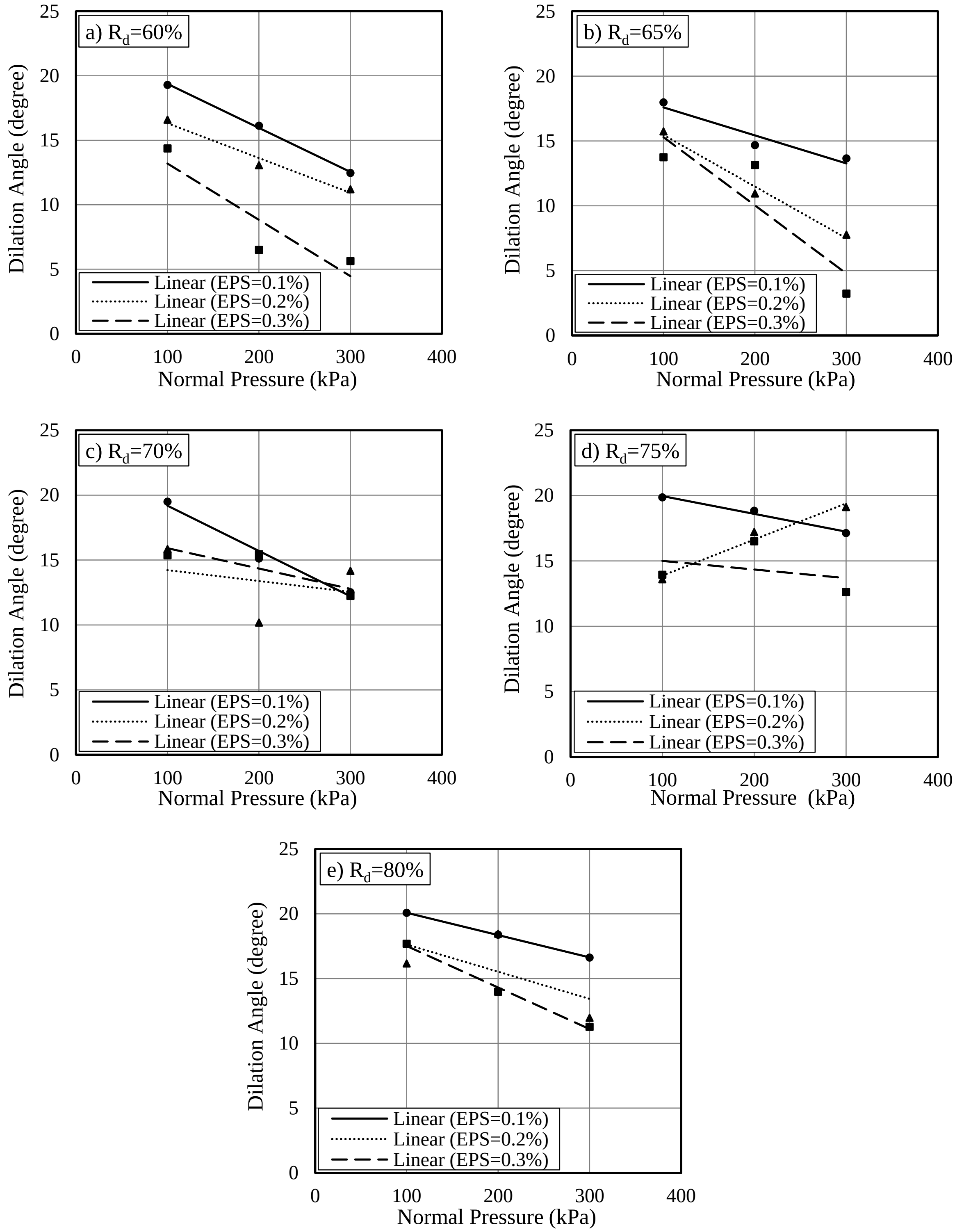

Figure 20. Variations of dilation angles for sand-EPS mixtures of different densities subjected to σ_n=100, 200 and 300 kPa.

Tables:

Table 1. Sand characteristics

Characteristics	Standard	Value
Max. dry unit weight, $\gamma_{max.}$ (kN/m^3)	ASTM D4253-16 [62]	15.43
Min. dry unit weight, $\gamma_{min.}$ (kN/m^3)	ASTM D4254-16 [63]	13.04
D_{10} (mm)		0.36
D_{30} (mm)		0.96
D_{60} (mm)	ASTM D422-63 [65]	2.10
Coefficient of uniformity, C_u		5.83
Coefficient of curvature, C_c		1.22
USCS		SP

Table 2. Physical and mechanical properties of EPS particulates

Characteristics	Value
Density (kg/m^3)	12.0
Compressive strength at 1% strain (kPa)	15
Compressive strength at 5% strain (kPa)	35
Compressive strength at 10% strain (kPa)	40
Flexural strength (kPa)	69
EPS particulate size (mm)	2-5

Table 3. Sand-EPS particulate mixtures investigated

R_D (%)	EPS (%)	Total mass (g)	Mass of soil (g)	Mass of EPS (g)
100	0.0	147.23	-	-
	0.1		117.67	0.11
80	0.2	117.78	117.55	0.23
	0.3		117.43	0.35
	0.1		110.29	0.13
75	0.2	110.42	110.20	0.22
	0.3		110.09	0.33
	0.1		102.96	0.10
70	0.2	103.06	102.85	0.21
	0.3		102.75	0.31
	0.1		95.61	0.09
65	0.2	95.7	95.51	0.19
	0.3		95.42	0.28
	0.1		88.15	0.08
60	0.2	88.23	88.06	0.17
	0.3		87.97	0.26

Table 4. Shear strength parameter for EPS blocks

Test No.	Φ (degree)	C (kPa)
Test 1	2.8	18.6
Test 2	2.9	17.7
Test 3	2.9	17.7

Table 5. Summary of direct shear test conducted on EPS blocks

Reference	Sample size (mm×mm× mm)	Density (kg/m^3)	Normal stress (kPa)	Shear strength parameters	
				Φ (degree)	C (kPa)
Padade and Mandal (2012) [69]	100×100×50	15 to 3	15 to 60	3 to 6	30.75 to 59.75
Özer and Akay (2016) [35]	Upper box: 100×100×25 Lower box: 150×100×25	18.4 and 28.8	10 to 40	8.9 to 10	26.2 to 49.8
AbdelSalam and Azzam (2016) [36]	100×100×50	20	10 to 40	Dry: 19 Wet: 33	Dry: 16 Wet: 12
Khan and Meguid (2018) [37]	100×100×40	15 to 35	18 to 54	9 to 10.5	28 to 55

Table 6. Summary of sand shear strength parameters at different relative densities

R_d (%)	Φ (degree)	C (kPa)
100	49	16
80	47	14
75	44	10
70	42	7
65	39	4
60	37	2

Biographies

- **Mahmood Reza Abdi** obtained his MSc and PhD degrees from Bradford University and the University of South Glamorgan, UK, respectively. He is currently an Associate Professor and the Head of the Soil Mechanics Laboratory at Faculty of Civil Engineering, K.N. Toosi University of Technology, Tehran, Iran. He has published many research articles on soil improvement in national and international journals and supervised many students of MSc and PhD during his career.

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- **Maryam Kazemi Abyaneh** obtained her BSc and MSc degrees in Civil Engineering and Geotechnical Engineering from K.N. Toosi University of Technology in 2017 and 2019, respectively. Her research interest is soil-geosynthtics interaction under pullout and direct shear modes. She is currently working in a geotechnical engineering company supervising various geotechnical projects.

- **Mahdi Safdari Seh Gonad** obtained his Bachelor of Science in Civil Engineering from Ferdowsi University of Mashhad in 2015 and subsequently achieved his Master of Science in Geotechnical Engineering from K.N. Toosi University of Technology in 2017. Following his academic achievements, he has been engaged in research and has served as a research assistant in the Soil Mechanics Laboratory at K.N. Toosi University of Technology in Tehran, Iran. He is particularly interested in geotechnical engineering specially soil improvement techniques such as soil-reinforcement and deep soil mixing.