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Research Article

Shear response and frictional properties of soil mixtures at different dry weight proportions

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ABSTRACT

On a specific purpose to investigate and evaluate an important mechanical property of natural soil mixtures being shear response and frictional characteristics, an extensive laboratory experimental program has been conducted that consisted of a series of direct shear tests on various soil mixtures, including sand (S), silt (M) and clay (C), at different dry weight proportions [(i) S:100% – M:0% – C:0%; (ii) S:50% – M:50% – C:0%; (iii) S:50% – M:0% – C:50%; (iv) S:50% – M:25% – C:25%]. The experimental findings of the testing program have shown that the measured values of two crucial engineering design parameters such as the peak (τ_{peak}) as well as the residual ($\tau_{residual}$) shear strengths for the soil mixtures are strongly influenced by the present soil type such that the detected values of τ_{peak}, $\tau_{residual}$ increase with an increase in sand content in the mixture whereas the attained values of τ_{peak}, $\tau_{residual}$ decrease with an increase in clay content in the mixture. Further, adding silt into sand-clay mixture improves strength characteristics such that the values of τ_{peak}, $\tau_{residual}$ become greater. On the other hand, adding silt into pure sand diminishes frictional resistance such that the values of τ_{peak}, $\tau_{residual}$ become lower. Consequently, it is seen that soil particle size (i.e. grain size) plays an important role on the shear strength behavior of the natural soil mixtures. Moreover, the displacement (δ_{peak}) required to reach peak shear strength (τ_{peak}) was also determined as a result of the direct shear tests. As such, the detected values of δ_{peak} become larger with higher clay content available in the mixture, while the obtained values of δ_{peak} become smaller with higher sand content existing in the mixture. Therefore, it is concluded that the higher the clay content, the mixture exhibits relatively more ductile shear behavior, whereas the higher the sand content, the mixture displays relatively more brittle shear response.

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INTRODUCTION

In nature, the occurrence and distribution of soils is such that the various types of soils can be found together as well as mixed at different weight proportions. In general, the engineering design methods and analysis parameters on evaluating the strength properties (i.e. bearing capacity) and deformation characteristics (i.e. elastic/plastic settlement under loading) have been developed for ideal soils such as pure sand or pure clays which, however, deviates from the reality. Research studies on these soils have progressed over the decades as performed on clean sands or pure clays both of which define distinct boundaries of a very wide spectrum of natural soils, and hence, sets limits on the prediction stress-strength-strain behavior (i.e. load-bearing capacity-deformation response) of soils under super-structural and/or infra-structural loading.

The ground soil such as sand, silt, and/or clay is the most important factor in engineering design and/or analysis as well as construction of environmental infrastructures that must wisely and technically be evaluated in the first place before performing building operations. This is regarding to the fact that those ground materials are utilized for the foundation of the environmental infrastructures that functionally transfer structural loads to the sub-ground. Therefore, in order to understand the engineering behavior and load-deformation response of those ground soils comprised of solely one type soil or mixture of different soil types, the geoenvironmental engineers are required to conduct laboratory and in situ tests so that their engineering response in terms of friction forces between those materials and reactions under stress and/or strain application could be evaluated. Depending on physical state and boundary conditions, those ground soils and their mixtures can display distinct shear behavior and frictional characteristics with different kinds and combinations of substances under different loading conditions. To this end, in the last few decades, the shear response and frictional properties of soil mixtures at different dry weight proportions have been taking attention of the researchers including Kuerbis et al. [1], Pitman et al. [2], Lade and Yamamuro [3], Thevanayagam et al. [4] and Murthy et al. [5]. Those previous research studies mostly focused on the influence of fine materials content (silt and/or clay) on the dynamic response of the soil mixtures. On the other hand, the direct shear characteristics and frictional properties under static loading conditions have received limited attentions such as Lupini et al. [6], Shakoor and Cook [7] and Georgiannou et al. [8]. In this regard, this study will extend the understanding on how the weight proportions and/or the type of soils in the natural soil mixtures affect stress – strain characteristics as well as peak and residual shear strength properties.

The reason for the laboratory investigations involving the detection of the shear response and frictional properties of soil mixtures comprised of different soil types such as sand, silt, clay being very rare in the literature is that the determination of the mechanical properties of such soil mixtures requires the use of specialized, precise and specific loading systems that can properly simulate field stress conditions. This type of specialized loading systems including ring shear device and triaxial device have only been utilized by a few researchers such as Lupini et al. [6] and Georgiannou et al. [8], respectively. Further, for micro-state response under loading, it was proposed by some researchers including Mollins et al. [9] that the fine-grained soils (e.g. clay, silt) and course-grained soils (e.g. sand) mixtures can inherently be existed in two characteristic states. As such, the fine-grained soils in the mixture at low confining stresses are able to swell against the surcharge and separate the course-grained soils particles to reach the same void ratio for a given surcharge as fine-grained soil alone, whereas; at high confining stresses, the fine-grained soil void ratio, after filling the sand pores, can become greater than the fine-grained soil void ratio in equilibrium with the surcharge stress, and the sand particles remain in contact.

As the artificial fine-grained (e.g. clay, silt) and course-grained (e.g. sand) soil mixtures increasingly preferred by the design engineers for geoenvironmental and geotechnical infrastructural applications to improve strength properties and enhance hydraulic characteristics, this study will provide a different perspective how and to what degree a fine-grained soil (e.g. clay, silt) could enhance a course-grained soil (e.g. sand) in terms of frictional properties and shear strength characteristics (i.e. being the most important mechanical property of soils for a clear as well as explicit understanding of the soil response against distinct loading conditions in the field) depending on the mass amount or the dry weight proportion of clay and/or silt being present in sand. Therefore, the material is predominantly comprised of granular soil such as sand; and accordingly, the amount of added fine-grained soil such as clay and/or silt is not large enough so that the mixture should not start to behave as anything other than sand in order to evidently observe and manifestly detect shear response and frictional properties as the sand dominates the engineering properties of the admixture material.

MATERIALS AND METHOD

Test Matrix

In order to investigate and evaluate an important mechanical property of natural soil mixtures that is shear response and frictional characteristics, an extensive laboratory experimental program has been conducted which consisted of a series of direct shear tests on various soil mixtures, including sand (S), silt (M) and clay (C) at different dry weight proportions (Table 1).

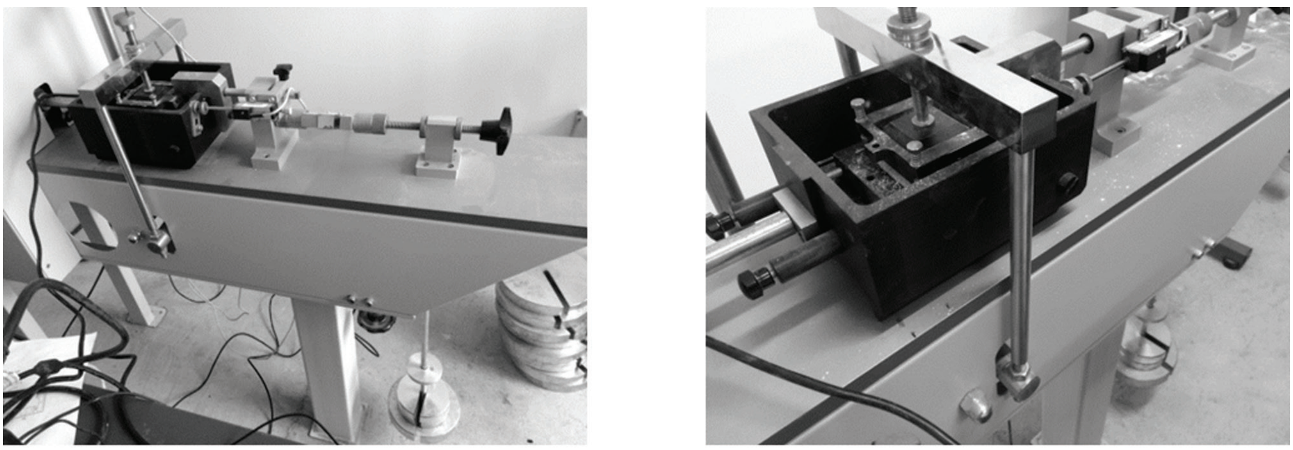
Testing Devices and Experimental Methods

In order to measure and evaluate shear response and frictional properties of soil mixtures at different dry weight proportions, the direct shear testing method [10] among different mechanical frictional strength test detection techniques were applied in the laboratory using an automated direct shear device (Figure 1). The entire shear box apparatus includes the loading devices and the sensors in addition to the shear box container.

Prior to preparation of soil mixture samples at different dry weight proportions (Table 1), soil specimens were placed in a shear box that consists of two stacked square pieces both of which having dimensions of 60 mm X 60 mm in plan to hold the soil mixture specimens. In other words, the shear box is a rigid metallic container in which the soil specimen is retained during the course of the testing. The total thickness of the shear box is 50 mm while the thickness of specimen within the box is 25 mm. The contact between those two square halves (pieces) of the shear box is at the mid-height of the specimen. Following the placement of the specimen in the shear box, the top cap was located, immobilized and restrained by a pin attached and fixed to a cross beam. Thereafter, the selected confining stress (i.e. normal stress) was applied vertically onto the soil specimen through the cross beam connected to the incremental weight placement mechanism compartment of the shear device. The selected added weights into this compartment were calculated based on the proposed normal stress intended to be applied during the test progress. Afterwards, the testing process was initiated by pulling laterally the lower part of the shear box so that the frictional response within soil specimen on a horizontal surface coinciding with the contact shear area in between two counterface shear box segments was measured in such a way that the shear behavior of every soil mixture samples was detected completely. That's to say, the shearing of the soil specimen is inducing horizontal strain on the test sample by displacing the top half of the box laterally with respect to the bottom half of the box at a constant rate of shearing deformation while measuring the

Table 1. Test Matrix

Test Specimen	1	2	3	4
Normal Stress, (σ) = 25 kPa	Sand (100%) – Silt (0%) – Clay (0%)	Sand (50%) – Silt (50%) – Clay (0%)	Sand (50%) – Silt (0%) – Clay (50%)	Sand (50%) – Silt (25%) – Clay (25%)
Normal Stress, (σ) = 50 kPa	Sand (100%) – Silt (0%) – Clay (0%)	Sand (50%) – Silt (50%) – Clay (0%)	Sand (50%) – Silt (0%) – Clay (50%)	Sand (50%) – Silt (25%) – Clay (25%)
Normal Stress, (σ) = 100 kPa	Sand (100%) – Silt (0%) – Clay (0%)	Sand (50%) – Silt (50%) – Clay (0%)	Sand (50%) – Silt (0%) – Clay (50%)	Sand (50%) – Silt (25%) – Clay (25%)



(a) (b)

Figure 1. Direct Shear Device **(a)**, Close up View of Shear Box **(b)**.

shearing force, the relative lateral displacement, and the normal displacement. The soil specimens were sheared to a horizontal displacement of 10 mm at a shearing rate 1 mm per minute (1 mm/min) until the sample fails prior to finalizing the test through a specified strain of ~15%. In direct shear tests, the failure surface in soil specimens tested is restricted to occur on a specific predefined surface called shear plane being horizontal as well as parallel to the shearing displacement.

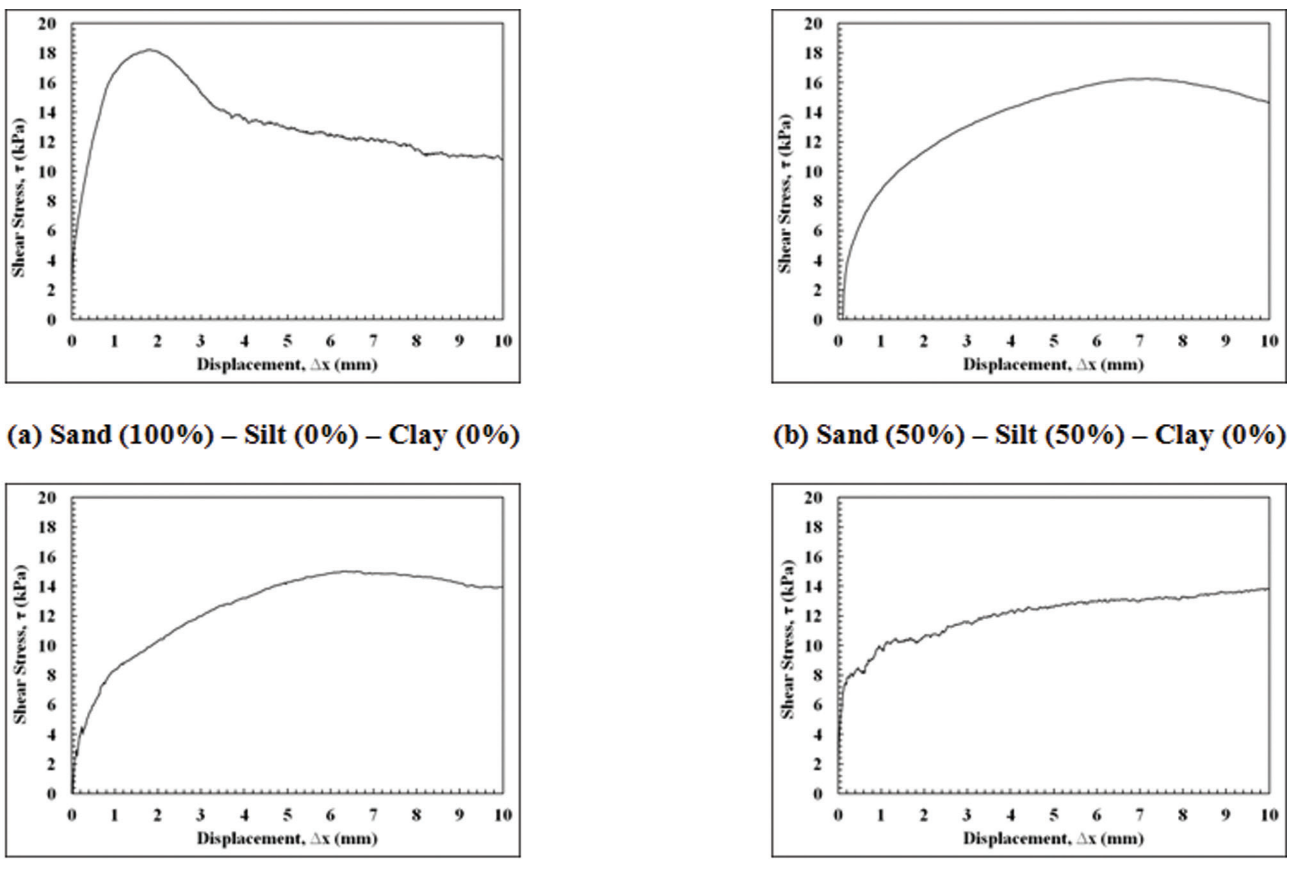
Theory and Calculations

The horizontal load applied or the shear stress measured as well as the lateral displacement moved (i.e. horizontal deformation produced) or the lateral strain induced was recorded at frequent time intervals by a controller program to determine stress-strength-strain curves or load-displacement plots for each confining stress or normal load. From each soil mixture at a specified dry weight proportion, several test specimens were prepared in order to be tested at various normal stresses so as that the failure envelopes (Mohr-Coulomb Failure Envelopes) demonstrating the shear response and frictional properties through two important strength properties (i.e. engineering design parameters) of soils such as soil cohesion (c) and internal friction angle (ϕ) were developed. To this end, the shear stress (τ) is correlated to the normal stress (σ) through a mathematical model (Equation 1) displaying the behavior of the generated Mohr-Coulomb failure envelopes as a result of direct shear tests. Then, the results of the tests on each specimen were plotted on a graph with the peak (i.e. maximum value) or the residual (i.e. large displacement constant value) frictional shear stresses (τ_{Peak}, $\tau_{Residual}$) on the ordinate (y-axis) and the normal confining stress (σ) on the abscissa (x-axis). As such, the y-intercept of the curve that best fits the test results through the regression analysis describes the cohesion (c) and the slope of the curve represents the internal friction angle (ϕ).

$$\tau = c + \sigma.\tan\phi \qquad (1)$$

EXPERIMENTAL FINDINGS AND RESULTS

The results of twelve direct shear tests on four distinct soil mixtures including different dry weight proportions of three different soils such as sand, silt and clay at three



(a) Sand (100%) – Silt (0%) – Clay (0%)

(b) Sand (50%) – Silt (50%) – Clay (0%)

(c) Sand (50%) – Silt (25%) – Clay (25%)

(d) Sand (50%) – Silt (0%) – Clay (50%)

Figure 2. Direct Shear Response of Soil Mixtures at Different Dry Weight Proportions (σ = 25 kPa).

different loading conditions (σ = 25, 50, and 100 kPa) will be presented in this section along with necessary explanations and discussions on the experimental findings.

Direct Shear Response

The direct shear response of soil mixtures at different dry weight proportions for different loading conditions of low stress level (25 kPa), medium stress level (50 kPa), and high stress level (100 kPa) are presented in Figures 2, 3, and 4, respectively. Regardless of loading condition, the largest direct shear resistance was observed in sand (100%) – silt (0%) – clay (0%) soil mixture (Figures 2a, 3a, 4a), while the smallest resistance was exhibited in sand (50%) – silt (0%) – clay (50%) soil mixture (Figures 2d, 3d, 4d) at different normal stresses of 25 kPa, 50 kPa, and 100 kPa, respectively. This infers that the addition of clay at substantial amount (50%) significantly influence the shear resistance of soil mixtures. On the other hand, the addition of silt into the mixture contributes the shear resistance such that the sand (50%) – silt (25%) – clay (25%) soil mixture (Figures 2c, 3c, 4c at 25 kPa, 50 kPa, and 100 kPa stress levels, respectively) displays higher frictional resistance compared to that of the sand (50%) – silt (0%) – clay (50%), whereas demonstrates lower frictional resistance under shearing in comparison to that of sand (50%) – silt (50%) – clay (0%) (Figures 2b, 3b, and 4b).

Furthermore, the post peak strength loss behavior was observed in only sand (100%) – silt (0%) – clay (0%) soil mixture (Figures 2a, 3a, 4a). In contrast, for all other soil mixtures due to the addition of silt and particularly clay, no notable frictional resistance loss with continued shear displacement was detected. In particular, with addition of clay into the mixture, a marginal strain hardening behavior was exhibited such that a minor shear resistance gaining response was occurred with continued shear movement at larger displacements (i.e. especially >5-6 mm) (Figures 2d, 3d, 4d). The shear response of soil mixtures has become relatively more ductile with addition of clay having high plasticity, while the response has displayed as brittle due to predominant amount of nonplastic material being sand available in the mixture, and particularly in pure sandy soil (compare Figures 2a with 2d; 3a with 3d; 4a with 4d). Moreover, the shear stress – horizontal displacement curves located at higher field (i.e. area) of stress – displacement space for all the soil mixtures by increasing normal stress level from 25 kPa up to 100 kPa. This shows that the

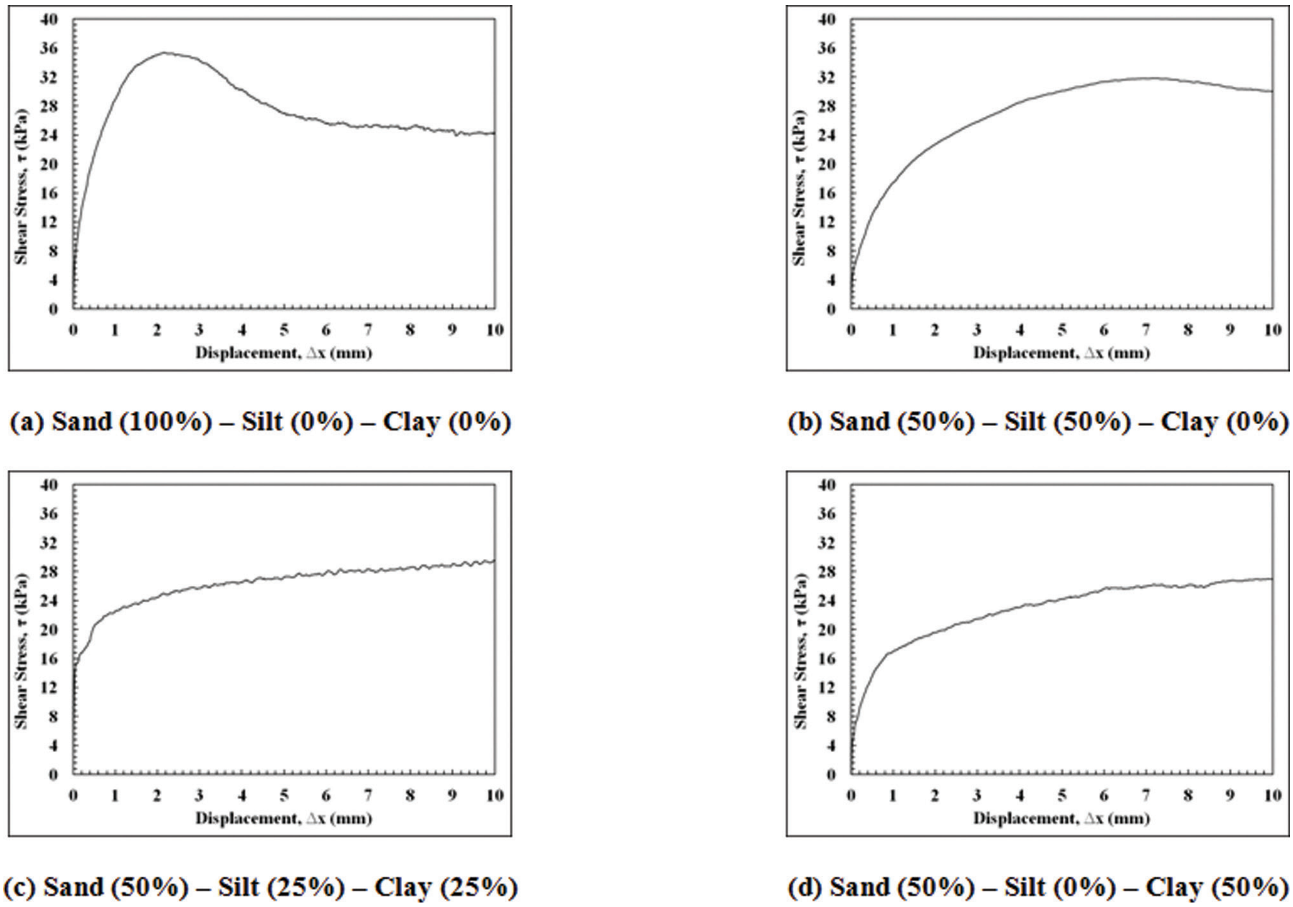


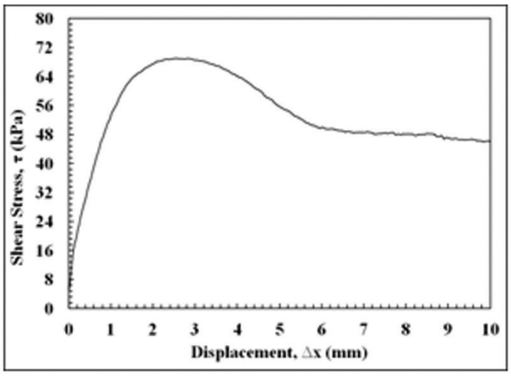
Figure 3. Direct Shear Response of Soil Mixtures at Different Dry Weight Proportions (σ=50 kPa).

larger the normal stress (i.e. loading), the greater the shear response and frictional resistance has developed regardless of dry weight proportions and/or soil types that exist in the mixtures (compare Figures 2a and 3a and 4a; 2b and 3b and 4b; 2c and 3c and 4c; 2d and 3d and 4d).

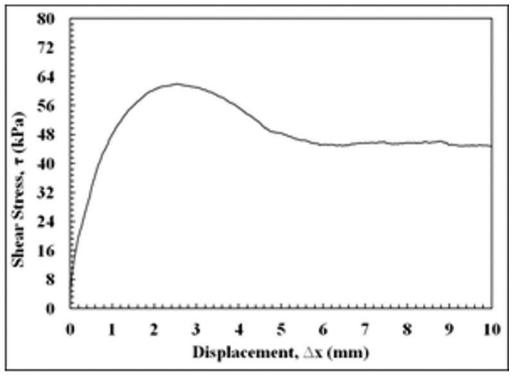
Similar results were observed and reported by Dafalla [11] that shear stress versus horizontal displacement graphs indicate bilinear behavior in general regardless of normal stress level within the initial elastic zone. Further, plastic softening generally develops and the slope of shear stress versus horizontal displacement plots flattens which indicates that a drop in the value of shear stress over a very wide range of horizontal displacement occurs compared to the elastic zone. Moreover, as known explicitly, the high confining stress causes the soil samples to be densely packed together, and thus, to become stiffer. On the other hand, the density and the stiffness of the mixture decrease with addition of plastic fines. This results from more compressible nature of clay and/or silt fines entrapped between sand contacts, and hence, the clay and/or silt fines deform and reshape themselves during isotropic compression because of which those fine particles cannot mobilize well-developed contacts along with the sand particles as the static stresses are not effectively transferred through the fines [12]. Furthermore, the stiffness degradation and shear strength of silty sands was studied by Lee et al. [13] in which a series of triaxial tests were performed on sand specimens containing different amounts of silt. The test results of the study showed that the shear strength of the admixture soil is strongly influenced by the silt content.

Comparative Analysis on Engineering Frictional Properties: Engineering Design Parameters

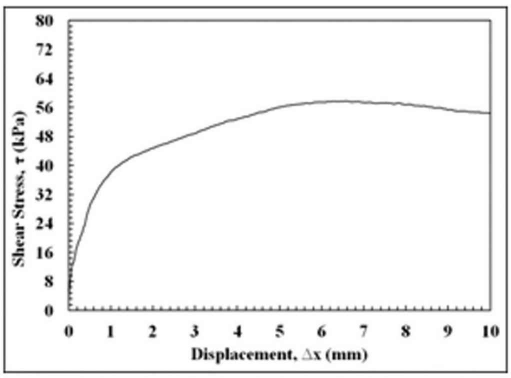
A further comparative analysis on engineering frictional properties including peak shear strength (τ_{Peak}), residual shear strength ($\tau_{Residual}$), and displacement required to reach peak shear strength (δ_{Peak}) was carried out in a purpose to extend the understanding on how those engineering design parameters could change due to variations in dry weight proportions of soil types that exists in natural soil mixtures. The comparison of peak shear strength (τ_{Peak}) for different soil mixtures are presented in Figure 5 for different loading conditions such as low normal stress level (σ = 25 kPa), moderate normal stress level (σ = 50 kPa), and high normal stress level (σ = 100 kPa). Regardless of loading condition, a similar behavior has been observed such that the largest



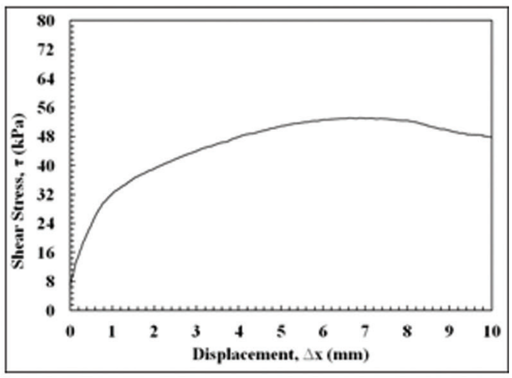
(a) Sand (100%) – Silt (0%) – Clay (0%)



(b) Sand (50%) – Silt (50%) – Clay (0%)



(c) Sand (50%) – Silt (25%) – Clay (25%)



(d) Sand (50%) – Silt (0%) – Clay (50%)

Figure 4. Direct Shear Response of Soil Mixtures at Different Dry Weight Proportions (σ=100 kPa).

τ_{Peak} was obtained for the sand (100%) – silt (0%) – clay (0%) soil mixture; whereas the smallest value of τ_{Peak} was detected for the sand (50%) – silt (0%) – clay (50%) mixture. In-between, the sand (50%) – silt (50%) – clay (0%) mixture exhibited relatively greater values than that of the sand (50%) – silt (25%) – clay (25%) mixture owing to the presence of silt in the sand-clay mixture. Consequently, it is pointed out that the addition of silt and clay into the pure sand results in a decrease of the τ_{Peak}; however the presence of silt in the mixture enhances the peak frictional strength compared to that of the solely sand – clay mixtures. On the other hand, as opposed to the substantial change displayed in the values of the peak shear strength (τ_{Peak}), a marginal change exhibited in the measured values of the residual shear strength ($\tau_{Residual}$) due to the inclusion of silt and clay into the pure sandy soil at all normal stress levels ranging from σ = 25 kPa up to σ = 100 kPa (Figure 6). This is attributed the fact that the large displacement (i.e. strain) frictional strength (i.e. $\tau_{Residual}$) is governed by the state of the shearing plane in addition to the soil particle size and gradation while the small strain frictional resistance is mostly regulated by the mean grain size and size distribution of soil particles. Furthermore, the order of sorting for the tested soil mixtures for the detected values of $\tau_{Residual}$ from the largest to the smallest is the same and corresponding with that of the measured values of τ_{Peak} from the largest to the smallest.

The comparison of displacement to peak (δ_{Peak}) for the tested soil mixtures prepared at different dry weight proportions is shown in Figure 7. At all normal stress levels of the direct shear testing, the measured values of δ_{Peak} were the smallest for the pure sandy soil among all the soil mixtures of the experimental program. Moreover, the values of δ_{Peak} for the pure sand were much dissimilar and isolated from those values detected for the other soil mixtures such that the magnitude of δ_{Peak} was approximately one quarter than that of the magnitudes for the other mixtures. For low and moderate normal stress levels of 25 kPa and 50 kPa, respectively, the higher the clay content the larger the values of δ_{Peak}, and furthermore, the addition of silt into the sandy soil can also result in an increase of the measured values of δ_{Peak} considerably. However, the influence of the clay is more remarkable and significant. On the other hand, for high normal stress level of 100 kPa, the detected values of δ_{Peak} were more or less similar for all soil mixtures including solely silt, solely clay, and/or both silt and clay except for the pure sand that was ¼ of the other values measured. This is attributed to the larger confinement of the soil mixtures

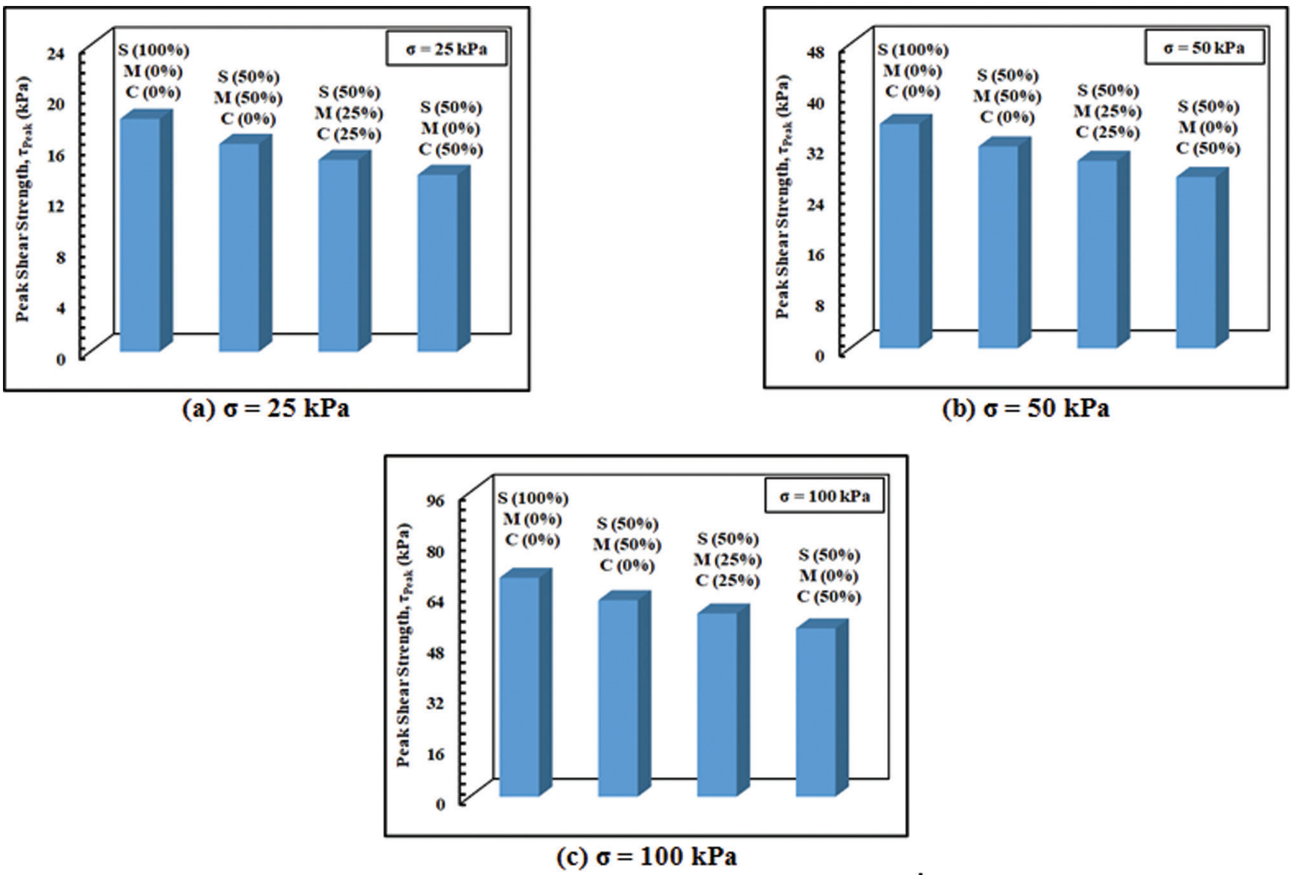


Figure 5. Comparison of Peak Shear Strength for Soil Mixtures at Different Dry Weight Proportions.

including two or three types of natural soil at high normal stress level of 100 kPa that results in the requirement of similar straining levels within the soil to be able to mobilize the peak state. Similar results were earlier presented by Georgiannou [14] such that the undrained response of sands with additions of particles of various shapes and sizes was examined extensively. As a result of a comprehensive testing program, it was evidently shown that when anisotropically consolidated specimens were sheared in triaxial compression as well as triaxial extension for which the specimens were prepared at their loosest state by following a depositional method called air pluviation, the additive materials into sand at contents greater than 2% by dry weight can dramatically change the undrained behavior of the host sand specimen. The shear response of pure sands and most mixtures tested was much smaller (weaker) and more contractive in triaxial extension than that of triaxial compression.

As seen in Figure 7, the displacement (δ_{peak}) required to reach peak shear strength (τ_{peak}) determined as a result of the direct shear tests became larger for the detected values of δ_{peak} with higher clay content available in the mixture, while the obtained values of δ_{peak} became smaller with higher sand content existing in the mixture. Further, the larger confinement of the soil mixtures including two or three types of natural soil at high normal stress level of 100 kPa resulted in the requirement of similar straining levels within the soil to be able to mobilize the peak state. Therefore, it is concluded that the higher the clay content, the mixture exhibits relatively more ductile shear behavior, whereas the higher the sand content, the mixture displays relatively more brittle shear response.

Moreover, the comparison of Mohr – Coulomb failure envelopes for the tested soil mixtures at different dry weight proportions for the Peak State and the Residual State are presented in Figures 8a and 8b, respectively. Linear behaviours for the peak state in the envelopes were exhibited for all the tested soil mixtures of the laboratory experimental program, where logarithmic (i.e. non-linear) behaviours were displayed for the residual state of all the soil mixtures. This results from larger confinement of the soil at high normal stress levels such as σ = 100 kPa that prevents the mobilization of the sufficient magnitudes of frictional strength (i.e. shear resistance) as expected within the soil due to shear displacement.

Similar results were reported by Kokusho et al. [15]. In their study, the undrained shear strength of granular soils with different particle gradations were examined from a

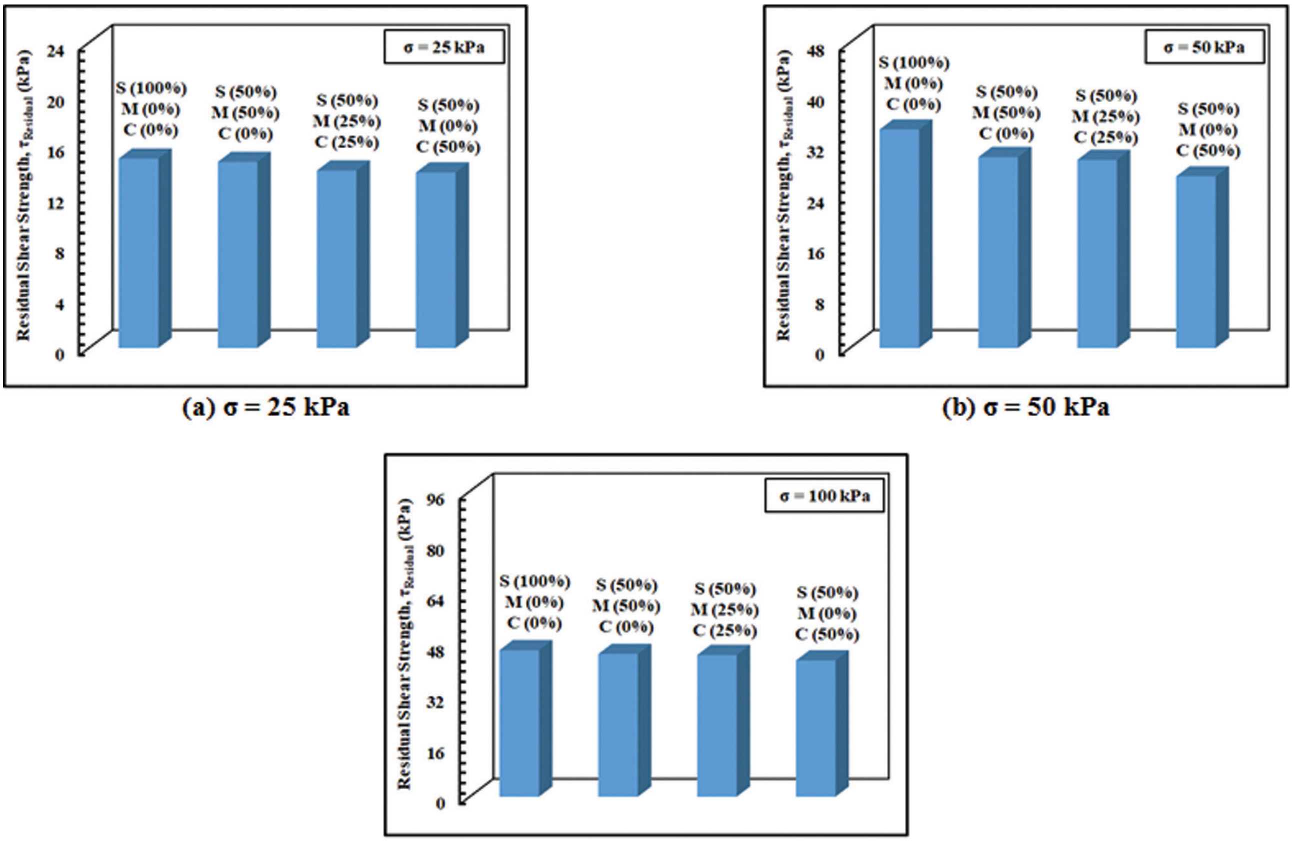


Figure 6. Comparison of Residual Shear Strength for Soil Mixtures at Different Dry Weight Proportions.

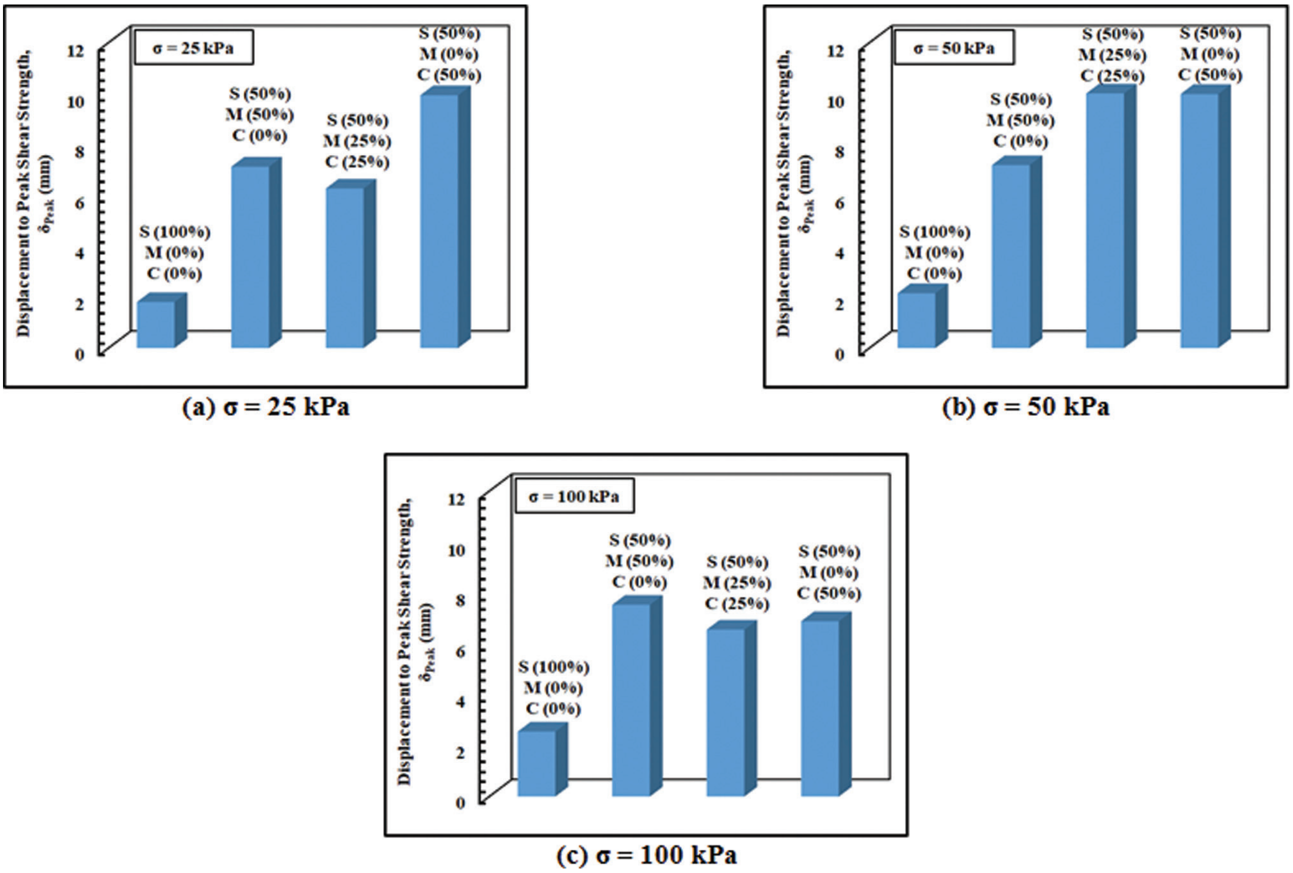


Figure 7. Comparison of Displacement to Peak for Soil Mixtures at Different Dry Weight Proportions.

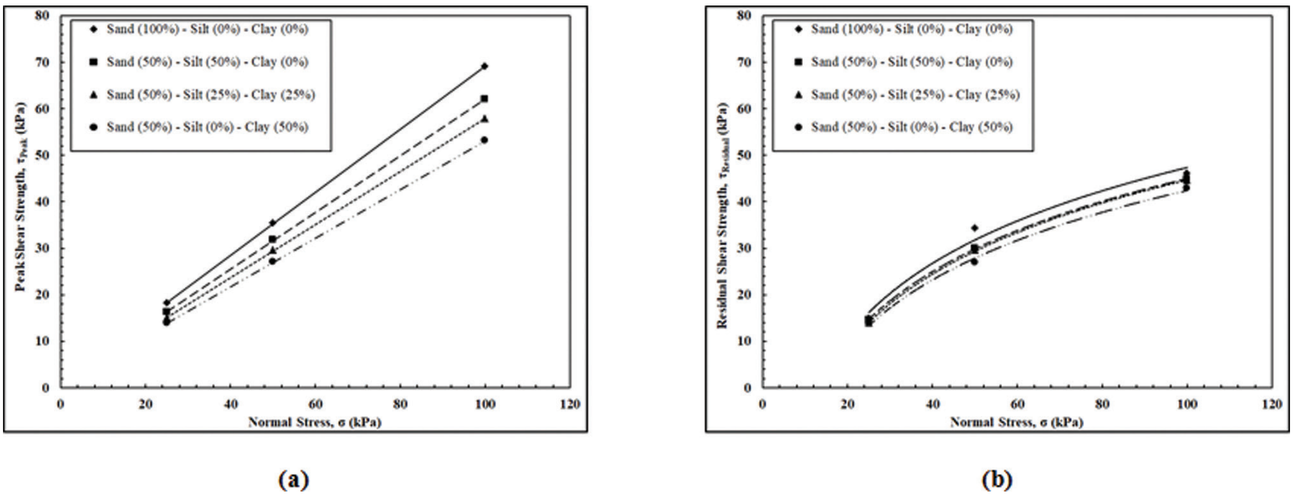


Figure 8. Comparison of Mohr – Coulomb Failure Envelopes for Soil Mixtures at Different Dry Weight Proportions: **(a)** Peak Shear Strength Failure Envelopes; **(b)** Residual Shear Strength Failure Envelopes.

series of laboratory experimental program. The undrained cyclic shear strength displayed a considerable change in the detected values at different confining stresses (i.e. different normal loading conditions). This shows that how different weight proportions of distinct soils being present in the mixture could influence the mechanical properties, including shear response and frictional characteristics, of admixture soils.

CONCLUSION

The experimental findings of the testing program and the results of analysis of the study have shown that the measured values of two crucial engineering design parameters such as the peak (τ_{peak}) as well as the residual ($\tau_{residual}$) shear strengths for the soil mixtures are strongly influenced by the present soil type such that the detected values of τ_{peak}, $\tau_{residual}$ increase with an increase in sand content in the mixture whereas the attained values of τ_{peak}, $\tau_{residual}$ decrease with an increase in clay content in the mixture. In addition, adding silt into sand-clay mixture improves strength characteristics such that the values of τ_{peak}, $\tau_{residual}$ become greater. On the other hand, adding silt into pure sand diminishes frictional resistance such that the values of τ_{peak}, $\tau_{residual}$ become lower. Consequently, it is seen that soil particle size (i.e. grain size) plays an important role on the shear strength behavior of the natural soil mixtures.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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