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Composite Sand–Clay Infrastructural Soil Fills: Characteristic Consolidation and Hydraulic Properties

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Abstract − In the design construction of infrastructural projects comprised of geotechnical applications, including composite soil fill layers, compacted sand-clay soil fills are widely preferred as barrier layers, particularly in solid waste landfills, to minimize leakage, to prevent leachate from entering into groundwater. When bentonite clay with high water absorption capacity and low hydraulic conductivity is mixed with sand possessing relatively enhanced frictional properties, greater shear strength capacity, an effective fill material exhibiting low sensitivity to frost, and low volume change in case of wetting, drying can be obtained. On the other hand, when montmorillonite clay is loaded, due to highly critical volumetric contraction or dilation characteristics (high compressibility nature of clay), the soil fill composed of sand-clay will significantly consolidate. This situation may cause differential settlement problems of infrastructural fills employed in geotechnical applications. In this regard, the load conditions (mechanical effects) and the environmental conditions (physicochemical effects) in the field control compressibility characteristics and consolidation properties of sand-bentonite clay mixtures. This will ultimately impact the desired stability conditions of sand-clay soil layers built for constructed infrastructural fill, resulting in a deviation from anticipated performance conditions. To this end, in this study, the specimens of sand-bentonite clay mixtures prepared with different contents of sand-bentonite clay were subjected to one-dimensional consolidation tests to investigate the effect of bentonite content used in the mixture on consolidation behavior, hydraulic properties, and effect of sand amount on rate of consolidation and on resulting compressive strength behavior.

Keywords − *Sand-clay mixtures, infrastructural soil fills, consolidation characteristics, hydraulic properties*

1. Introduction

The engineered infrastructural soil fills, designed and constructed by mixing and compacting sand and bentonite clayey soils, are nowadays used as clay lining layers in solid waste storage landfills and as a barrier protection layer in high-grade nuclear waste storage areas, and additionally, used frequently in ponds where mine waste is stored as well as for the construction of dams. The primary reason for selecting layers including clay in constructing these infrastructures is that the lining layer built by soil fill containing clay, having very low permeability, provides impermeability to this barrier layer. On the other hand, the soil fill, including the clay lining layer, should be able to maintain its strength and bearing capacity when subjected to the stresses under the action of surficial loads that the infrastructural application will be exposed to during its service life, and besides, should not exhibit time-dependent settlement problems under long-term loading.

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Under loads, imposed forces, and induced stresses, all soils will settle, causing the settlement of structures and infrastructures founded on and within them. If the settlement is not kept to a tolerable limit, the desired use of the structure or infrastructure might be impaired, and the design life of the structure or infrastructure could be reduced. Structures or infrastructures might settle uniformly or nonuniformly. The latter condition is called differential settlement and is often the crucial design consideration. In general, the development of plastic consolidation settlement usually leads to the mobilization of hazardous differential settlement resulting in risky design issues. As a response and meet this important phenomenon, in order to extend understanding of the characteristics of consolidation deformation and the resulting settlement properties as well as the hydraulic conductivity behavior of soil fills constructed using sand-clay mixtures, within the scope of this research study, a comprehensive experimental program including a series of consolidation tests were carried out in the laboratory on the sand-bentonite admixtures with different sand contents by means of which the consolidation behavior and hydraulic conductivity characteristics of those soil mixtures were investigated.

2. Relevant Literature and Background

The bentonite clay, which consists of a large amount of montmorillonite minerals, provides high water absorption capacity and low hydraulic permeability to the barrier layer. At the same time, the sand soil increases the strength properties of the layer constructed by mixing and compacting sand and clay. The hydraulic conductivity of the compacted clays is generally less than 10^{-7} cm/s. In the condition that sandy soils with high hydraulic conductivity are mixed with fine-grained soils such as bentonite clay with low permeability, their conductivity properties decrease considerably [1]. Therefore, in constructing infrastructural fills, in case there is insufficient clayey soil to be utilized nearby, the compressed sand-bentonite mixtures will be a good alternative for barrier layers conventionally constructed using only compressed clay [2].

Bentonite is a clay type containing montmorillonite group mineral. The metamorphosis of volcanic ash forms montmorillonite minerals, and its mineralogical structure is composed of a gibbsite layer between two silica layers. Small amounts of cations and large amounts of water molecules exist between each montmorillonite layer [3]. High cation exchange capacity, low hydraulic conductivity, high swelling potential, and large surface area constitute the characteristic structure of the montmorillonite mineral [4]. Due to the very weak bonds between the Montmorillonite layers, excessive volume changes are observed in the clays containing this mineral when they take in water. Therefore, bentonites containing this mineral have a high swelling potential. Since it contains Montmorillonite minerals, bentonite clay has high water absorption capacity and low hydraulic permeability. In addition, the interaction of pore water and grains surrounding bentonite grains greatly affects the bentonite behavior [1].

The materials to be used in the clay coating layer in modern solid waste landfills should have low hydraulic conductivity, low compression tendency, sufficient swelling potential, high strength, and the quality to prevent water leakage [5]. The most important factor determining the time-dependent performance of these infrastructures is how long the substances in the leachate are delivered to the natural ground or groundwater under the barrier layer. Therefore, hydraulic imperviousness is the most important physical property that determines the performance of barrier layers [6]. Another feature of clay layers that should be considered in modern landfills is the long-term compressibility of the clay layer under load. In these infrastructures, serious settlement problems may occur under prolonged loading. Examining the consolidation properties of the bentonite-sand mixtures is important for the settlement analysis of the infrastructure. In addition, the physical, chemical, and mineralogical properties of bentonite clay affect the consolidation properties of bentonite soil mixtures [7].

For this reason, to date, consolidation parameters such as compression index (C_c), coefficient of consolidation (c_v), and reloading index (C_r) of bentonite-soil mixtures have been studied by many researchers. Furthermore, Mishra et al. [7] applied consolidation tests on 15 different bentonite-soil samples prepared by using various types of bentonites to investigate the effect of physical, chemical, and mineralogical properties of bentonite on bentonite-soil mixtures. As a result of the experimental program, they observed that the C_c increased directly proportional to the plasticity index (PI), and the c_v for all bentonite types, for which the experiment was performed, decreased with the increasing liquid limit (LL) value. They also observed an increase in cv under increasing consolidation pressure. They explained and reasoned this with experimental findings that bentonite-soil mixtures were consolidated at a higher rate under a higher load.

In another study examining the consolidation properties of bentonite-soil mixtures, they investigated the changes in volumetric compression coefficient (m_V), consolidation coefficient (c_v), and recompression index (C_r) in the presence of different concentrations of NaCl and $CaCl_2$ salt solutions in the environment. They observed that when the salt concentration in the environment was increased, the C_c and m_V decreased, whereas the c_v increased. Further, it has been stated that the c_v decreases under increasing consolidation pressure without considering the salt concentration. The m_V increases under increasing consolidation pressure until a certain maximum value is reached and decreases after this maximum value. They attributed the decrease in the consolidation coefficient, $c_{v,}$ under increasing pressure to the mechanisms controlling the compression behavior of bentonite-soil mixtures [8].

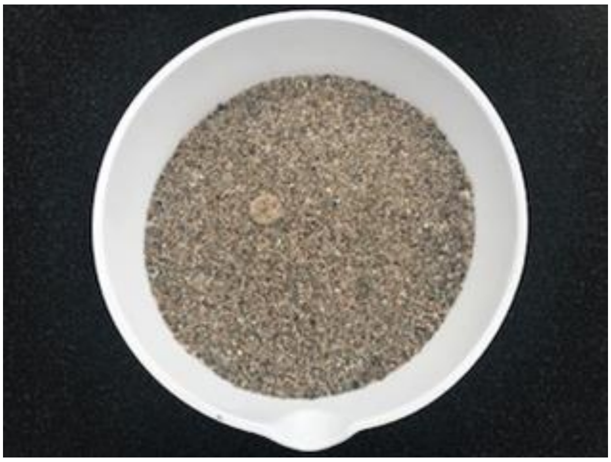
Moreover, a study examining the consolidation behavior of different clayey soils containing montmorillonite, kaolinite, and illite minerals detected that the m_V decreased with the increase in consolidation pressure [9]. Furthermore, a recent research study [10] showed that the compressive strength of the admixture soils mixed with pond ash, including sand, enhanced with an additional contribution to improving hydraulic characteristics. Another important research work [11] demonstrated that as the coral sand content increased in the admixture soils, including fine and course materials, the peak shear strength and the critical state shear strength decreased marginally. Moreover, the influence of sustainable utilization of chemically depolymerized polyethylene terephthalate (PET) on the sand-bentonite clay liners was revealed by Alok and Sumi [12]. The findings of this study suggested that a mechanism of interaction exists between sand-bentonite admixtures and the chemically depolymerized form of polietilen tereftalat (PET) polymers.

Further, an insightful research study to extend understanding of the volume change behavior of binary sand-clay mixtures was conducted by Sun et al. [13]. The volumetric contraction was reported to increase with increased stress level or fine content such as clay proportion in the mixture. Lastly, one-dimensional cyclic loading tests on sand-clay mixtures were performed by Khoshghalb et al. [14] to examine the settlement of the test samples. Their research findings revealed that the admixture soil settlement decreases while the time required to complete the primary consolidation increases. In light of the research findings until the present time discussed throughout the introduction and literature review section herein, to this end, a purpose is to fill the gaps among those earlier studies as well as to explore contradictions and uncover discrepancies; in this current study, an extensive laboratory testing program has been conducted such that a series of consolidation tests were applied to sand-bentonite mixtures containing different sand content ranging from 10% up to 40% by dry weight. This way, sand-bentonite admixture soils' consolidation behavior, properties, and hydraulic permeability characteristics were investigated. Additionally, a further statistical analysis was comparatively carried out on the test results and experimental findings to investigate the correlational binary behavior of the resulting engineering properties and design parameters. This was intentionally conducted to quantitatively evaluate the resulting behavior detected and examine important engineering characteristics of sand-clay mixtures based on the increased amount of granular soil (i.e., sand) in the admixture soils.

3. Experimental Materials and Methods

3.1. Testing Materials

The sandy soil preferred to be used in the laboratory experimental program was natural beach sand and an industrial bentonite was selected to be utilized as clayey soil. Figure 1 shows the images of the testing materials, including beach sand and bentonite clay.

(a) **(b)**

Figure 1. Soil types used in the testing program: **(a)** Bentonite clay, **(b)** Beach sand

The bentonite clay used in the experimental program is an absorbent swelling clay consisting mostly of montmorillonite. It is classified as high plasticity clay (CH) based on the Unified Soil Classification System (USCS) soil classification system. As such, the powdered form sodium bentonite clay tested in the laboratory program comprises the montmorillonite group of minerals. The physical and index properties of the bentonite clay utilized in the testing program consist of specific gravity (G_s) of 2.74, liquid limit (LL) of 295%, plastic limit (PL) of 57%, plasticity index (PI) of 238%.

A Sieve analysis test was performed for the sand soil to determine the grain size distribution of the sand sample that constitutes the sand-clay admixture specimens to be subjected to the consolidation test. After preparing dry test specimens with the predetermined sand and bentonite content (i.e., dry weight proportions), the admixture specimens were ready for the consolidation test by kneading (plasticizing) with water. The experimental program took a substantial amount of time such that each consolidation test was completed in six days. The important index properties of sand and clay soils are provided in Table 1 below.

Table 1. Important index properties of sand and clay soils

Soil	PL	LL	e_{min}	e_{max}	G_s
Sand	−	−	0.59	0.76	2.80
Clay	57%	295%	1.9	18.2	2.74

3.2. Experimental Device

Consolidation is the time-dependent settlement of soils resulting from water expulsion from the soil pores. This important plastic deformation response (i.e., settlement behavior) of particularly fine-grained soils, including clays, can be measured. The resulting detected behavior can be evaluated using an oedometer (i.e., 1D consolidation device). That is to say, a floating ring cell consolidometer in which the ring containing the soil sample is unrestrained in the container is utilized in the laboratory to perform consolidation tests on clayey soil and admixture specimens (Figure 2). A linear variable differential transformer (LVDT) was employed in the system to measure vertical displacement in evaluating the deformations developing in the soil specimen under the application of load during the tests. Enclosed in a stiff metal ring, a disk of soil was placed between two porous stones in a cylindrical container filled with water (Figure 2b). A metal load platen mounted on top of the upper porous stone transmits the applied vertical stress to the soil sample. In this way, the soil specimen inside the ring was loaded and the resulting vertical displacement was measured and recorded in the computer by testing controller program.

(a) **(b)**

Figure 2. Consolidation device: **(a)** General view, **(b)** Close up view

3.3. Experimental Procedures

3.3.1. Sieve Analysis

Before preparing the sand - clay mixtures, sieve analysis was performed to draw the sand sample's grain size distribution curve and determine the grain size criteria [15]. ASTM sieves, including 4.76 mm (No.4), 2 mm (No.10), 1 mm (No.40), 0.420 mm, 0.250 mm (No.60), and 0.076 mm (No.200) were used in the tests. Test specimens of 200 g were partitioned off from the sand sample by following the quartering method before starting the dry sieving process. The test specimens were kept in water to which Sodium Hexameta Phosphate $(NaPO_3)_6$ was added for one day and washed under clean water on a 0.076 mm sieve to remove possible salt and lime. The sand test specimens, left to dry for 24 hours in an oven heated at 110°C, were subjected to sieving. A sieve shaker device was used during the sieving process followed by manual sieving by hand to ensure particle sorting perfectly for better rating. After the weight of the soil remaining on the sieves, which were arranged with the largest mesh opening at the top, was measured on an electronic scale with 0.1 g precision as specified in the relevant regulation, the percentage of the sample passing through each sieve (% P) was calculated. Figure 3 shows the grain size distribution curve of the sand sample tested. Based on the results of sieve analysis tests performed in the laboratory, the sample was determined as SP (poorly graded sand) according to the ASTM classification system. Further, the grain size distribution properties of sand specimens used in the laboratory experimental program are tabulated in Table 2.

Furthermore, the tests with soil admixtures at specific proposed dry weight proportions are generally performed with laboratory-constituted specimens. A special soil mixer achieved relatively uniform and homogeneous soil specimen admixtures. Accordingly, the test specimen preparation technique of air pluviation is an extensively and commonly preferred methodology among other different sample preparation techniques developed to simulate in-situ field conditions. Moreover, the air pluviation methodology provides more uniform and homogeneous specimens than the other techniques [16]. Similarly, Rad and Tumay [17] concluded that air pluvial compaction is the best reconstitution method for soil admixtures, including granular soils such as sand and cohesive soils such as clay, to simulate the formation of soil admixture deposits in the field.

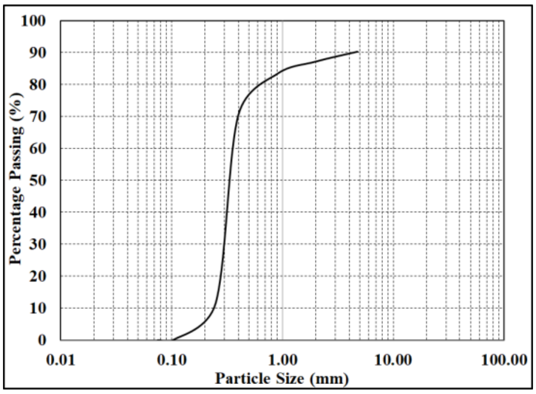


Figure 3. Particle size distribution for sand specimen tested

Table 2. Grain size distribution properties of sand specimen

D_{10} (mm)	D_{50} (mm)	C_u	C_c
0.22	0.31	2.27	0.87

3.3.2. Oedometer Test and Testing Program

The physical, chemical, and mineralogical properties of bentonite clay influence consolidation properties and, hence, the settlement behavior of sand-bentonite mixtures. This study performed a series of one-dimensional consolidation tests in the laboratory to determine the settlement properties and consolidation engineering parameters (c_v, m_v, α_v, C_c, and C_r) of sand-bentonite mixtures [18, 19]. Based on Terzaghi's one-dimensional consolidation theory, the one-dimensional consolidation experiment aims to find the consolidation parameters by providing vertical drainage under the controlled, increased vertical stress in the soil specimen where the horizontal deformation is prevented [20-23]. Sand-bentonite soil admixtures were mixed with distilled water and kneaded, and thereafter, the test specimens with a thickness of 2.50 cm and a diameter of 6.0 cm were prepared. Test mixture specimens prepared from sand-bentonite admixture samples were taken into the consolidation ring, the inner wall coated with Vaseline to minimize the lateral friction effect. The top and bottom of the test specimens in the consolidation ring were enclosed by filter papers and porous stones and kept in purified water for 24 hours to ensure purification from air voids and dirt residue. The floating ring consolidation cell is filled with purified water to enable full saturation of the test specimen after the placement of the consolidometer cell in the experimental set-up prior to the initiation of the test. The measurement intervals followed during the consolidation tests and the dry mass proportions of sand-bentonite mixtures tested are given in Tables 3 and 4, respectively.

Table 3. Data acquisition time intervals during consolidation tests

Reading No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Time (min.)	0.05	0.1	0.2	0.25	0.5	1	2	4	8	15	30	60	120	240	480	960	1440

Table 4. Dry mass proportions of sand-bentonite mixtures

Mass Proportions	**1**	**2**	**3**	**4**
Sand	10%	20%	30%	40%
Bentonite	90%	80%	70%	60%

4. Results and Discussion

Figure 4 shows the variation of the coefficient of consolidation (c_v) found for different sand contents under increasing consolidation pressure. In all mixtures, the c_v increased with increasing load while t_{90} decreased. Samarasinghe et al. [24] reported that the value of c_v for pure bentonite clay containing montmorillonite-type minerals decreases under increasing pressure, while it increases for sandy clay. Additionally, Mishra et al. [7] observed increased c_v as the consolidation pressure increased due to the consolidation tests performed on 15 different bentonite-soil samples. This can be explained by pure bentonite and sand-bentonite mixtures' consolidation behavior is completely different due to micro-structural inherent characteristics.

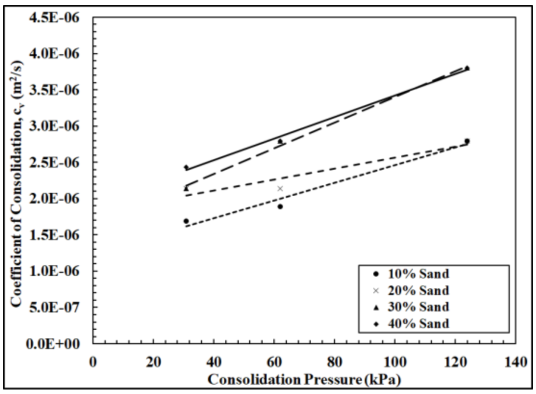
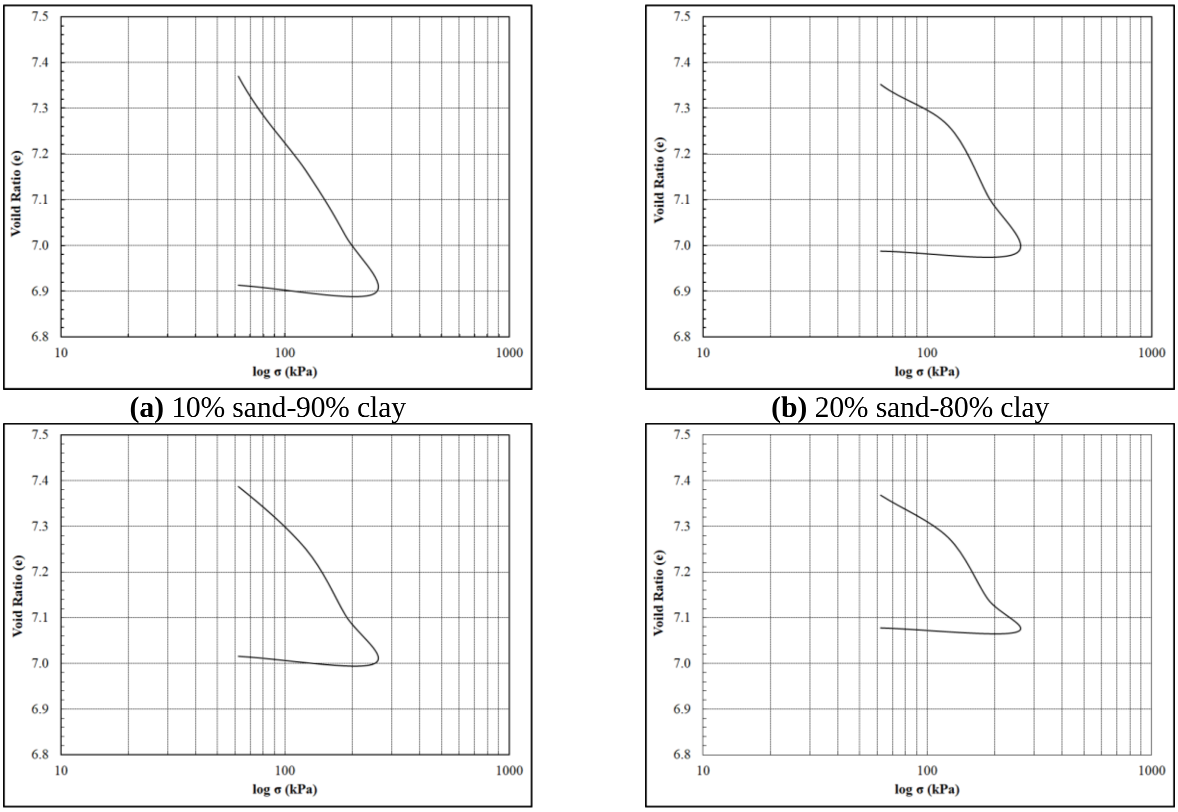


Figure 4. The variation of the coefficient of consolidation (c_v) with the consolidation pressure

Furthermore, while the consolidation behavior of pure bentonite depends on long-term repulsive and attractive forces based on physicochemical factors, the consolidation behavior of sand-bentonite mixtures mostly depends on mechanical effects that can result in c_v changing directly proportional to the increasing consolidation pressure [9]. Therefore, the results obtained from most of the specimens in this study are compatible and can be related and concerned with the aforementioned mechanical effects. Regardless of sand content, a linear increase in the values of cv was observed with an increment in pressure. As such, the higher the sand content for the specimens containing 30% and 40% sand by dry mass, the larger the increase in the values of c_v exhibited, while the relatively smaller increase in the values of cv displayed for the lower sand content specimens including 10% and 20% sand by dry mass. This concurs with the prevailing observations of previous researchers, including Robinson and Allam [9] and Mishra et al. [7]. In a purpose to investigate the compressibility characteristics of sand-clay mixtures at different dry weight proportions (10%-90%, 20%-80%, 30%-70%, and 40%-60%), the void ratio (e) on linear scale versus pressure (σ) (i.e., normal stress) on logarithmic scale semi-logarithmic curves were developed as a result of the obtained experimental measurement data from the entire testing phases of oedometer tests as presented in Figure 5. Accordingly, the compressibility characteristics of clayey soils containing various sand contents varying from 10% up to 40% and the compressibility response under increasing pressure can be deeply understood from the curves shown in Figure 5.



(a) 10% sand-90% clay **(b)** 20% sand-80% clay

(c) 30% sand-70% clay **(d)** 40% sand-60% clay

Figure 5. Void ratio (e) versus log (σ) curves: Compressibility characteristics of sand-clay mixtures at different dry mass proportions

For one-dimensional consolidation, the volumetric strain controlling consolidation settlement in the field is analogous and equivalent to the vertical strain governed by the change in void ratio under induced load. In this regard, the e versus log(σ) curves have been developed and utilized to extend understanding of the compressibility properties and, thus, consolidation settlement characteristics and load response. Furthermore, the decrease in the void ratio (Δe) resulted from incremental pressure - that could be related to the volumetric strain (ε_V) mobilized under loading reduced owing to the increasing sand content in clayey soil, and thus, enabling relatively greater bearing resistance against loading as well as providing higher strength response. This is attributed to the micro-inherent characteristics of admixtures such that relatively improved graded grain distribution of sandy clays as compared to pure clays containing one predominant soil mineral size facilitates the re-orientation of sand-particles and clay minerals for the ease and reformed re-organization of admixture micro-structure. In this way, the relatively denser soil is obtained with increasing sand proportion, resulting in less decrease in void ratio under identical pressure increment which controls the degree and severity of consolidation settlement through the volumetric strain displayed under loading in the field. Additionally, the increase in mass proportion of relatively rigid sand particles compared to weak, powerless clay minerals in the admixture enhances the sandy clays' overall bearing capacity, including greater sand contents.

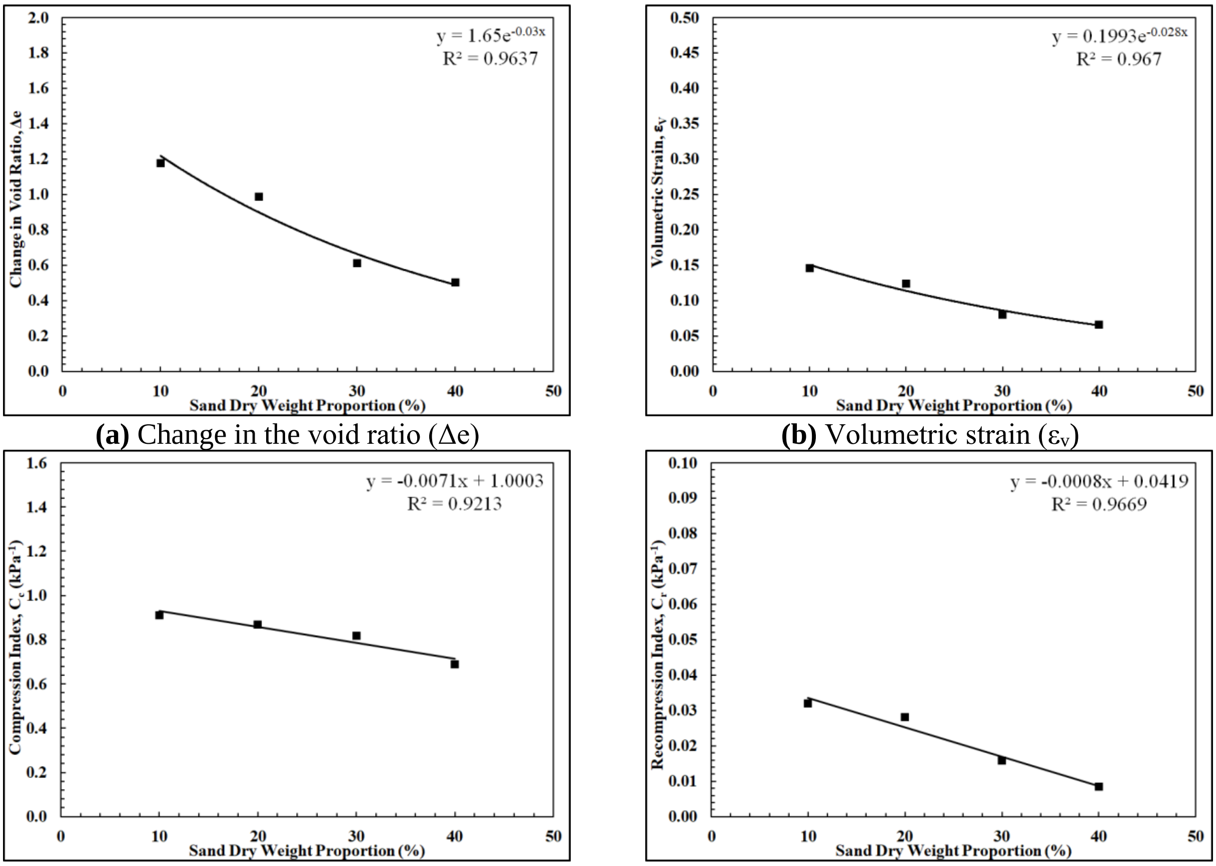
5. Further Statistical Analysis on Experimental Findings

Consolidation is a time-dependent soil settlement resulting from water expulsion from the soil pores. As such, consolidation is the change in the volume of fine-grained soil caused by the expulsion of water from the voids and the transfer of stress from the excess pore-water pressure to the soil particles that result in the mobilization and progression of settlement of soil fills in the field for particularly designed and constructed in infrastructural applications. In this regard, the ultimate magnitude as well as the rate of consolidation settlement initiated, progressed, and augmented inside soil fills in the field within the body of infrastructural applications are technically governed and can quantitatively be evaluated by accurately identifying consolidation engineerings design parameters such as Δe, ε_V, C_c, C_r, α_v, m_v, c_v, and k and properly investigating their variation with increasing sand content so as that the consolidation characteristics and hydraulic behavior of soil fill under loading, most of which are designed and constructed by utilizing sandy clays in the field, could be unveiled. Within this context, the variation in compressibility properties of sand-clay mixtures as a function of sand content are presented in Figure 6 to provide statistical analysis on the detected behavior with a change in the amount of sand available in clayey soil.

After load application, the onset of a decrease in the volume of void space occurs in the soil that can be measured and quantified by the change in void ratio (Δe). The degree and severity of this variation in Δe with an increase in sand content is shown in Figure 6a such that an exponential decrease in the resulting value of Δe displayed as a function of sand dry weight proportion. The change in the void ratio (Δe) is related to the volumetric strain (ε_V) developed in the soil due to load application, and that is concerned with the extent and intensity of consolidation settlement mobilized in the field under forces or stresses. In order to extend the understanding of the amount of consolidation deformation taking place within sandy clays in the field, the variation in volumetric strain (ε_V) with increasing sand content is demonstrated in Figure 6b such that an exponential decrease with an increase in sand dry weight proportion in the admixture exhibited.

As previously mentioned, the compression index (C_c) is the slope of the virgin line in the semi-logarithmic void ratio versus the pressure plot. The term expresses and demonstrates the consolidation settlement and compressibility that will occur under the applied pressure in the vertical direction. Accordingly, the compression index (C_c), as well as the recompression index (Cr), were determined from the generated e-log(σ) curves as earlier presented in Figure 5. The variation in C_c and C_r with increasing sand content in clayey soil is shown in Figures 6c and 6d, respectively. It was observed that there occurs a linearly decreasing behavior in the values of both C_c and C_r with an increment in sand content from 10% up to 40%. The decrease in compression indices with increasing sand content indicates the reduction in compressibility in sandy, clayey soils when the weight proportion of sand becomes larger within the admixture.

The statistical analysis of the detected behavior revealed an inverse proportionality between the compressibility engineering parameters, including Δe, ε_V, C_c, C_r, and the amount of sand available in clayey soil. This highlights how the consolidation characteristics of clayey soils are changed owing to sand inclusion in such a way that the compressibility of clayey soils reduces and becomes relatively more resistant against loading in the field, enabling less consolidation settlement and lower magnitude of deformations mobilized under stresses. Therefore, due to increased sand content, the sandy soil will provide greater bearing capacity and facilitate larger strength and durability against the induced forces/loads in the infrastructural applications. As seen in Figures 6a through 6d, the results of statistical analysis for the behavior investigated for the compressibility engineering parameters such as Δe, ε_V, C_c, and C_r are in good agreement between distinct data points and continuous regression with relatively high values of coefficient of determination (R^2) are demonstrated. Further, the detected values of Δe, ε_V, C_c, and C_r at different sand contents (i.e., dry weight proportions) are tabulated in Table 5.



(a) Change in the void ratio (Δe) **(b)** Volumetric strain (ε_v)

(c) Compression index (C_c) **(d)** Recompression index (C_r)

Figure 6. The variation in compressibility engineering parameters of sand-clay mixtures per sand content: statistical analysis on the detected behavior

Table 5. The detected values of Δe, ε_V, C_c, and C_r at different sand contents

Sand Content (%)	Δe	εV	C_c (kPa^{-1})	C_r (kPa^{-1})
10	1.1761	0.1457	0.9108	0.0320
20	0.9875	0.1239	0.8682	0.0281
30	0.6113	0.0803	0.8190	0.0158
40	0.5017	0.0663	0.6892	0.0084

The change in the void ratio (Δe) developed and, similarly, the volumetric strain (ε_V) generated during consolidation settlement reduced 50% to 60% owing to the addition of sand up to 40% by dry weight. Furthermore, the compression index (C_c) and the recompression index (C_r) diminished by 35% and 65%, respectively, due to the inclusion of sand up to 40% by dry weight into the clayey soil.

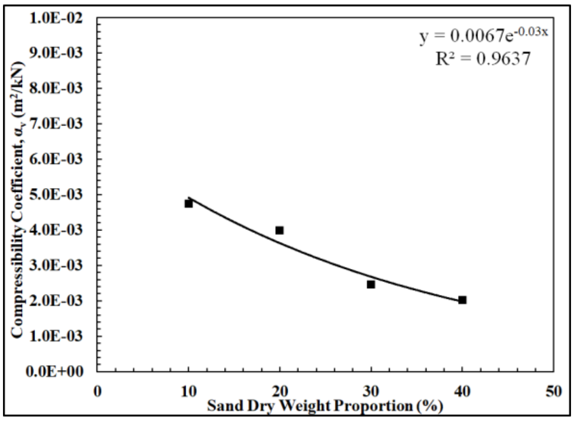
The variation in consolidation characteristics and hydraulic properties of sand-clay mixtures per sand content is presented in Figure 7 for various consolidation and hydraulic conductivity engineering design parameters based on further statistical analysis of the investigated behavior as a function of sand dry weight proportion. Accordingly, the compressibility coefficient (α_v) is the ratio of the reduction in the volume of void space (Δe) to the change in vertical pressure (i.e., load per unit area) detected from the plot of void ratio versus pressure curves. The change in α_v as a function of sand weight proportion in the admixture is given in Figure 7a. The statistical analysis of the investigated behavior has shown an exponential decrease with a relatively high coefficient of determination (R^2 = 0.9637) due to an increase in sand content in the sandy clay exhibited.

Furthermore, the coefficient of volume compressibility (m_v) defines and represents the volumetric strain developed corresponding to the unit stress increase in the consolidating clay soil layer. The variation in m_v concerning the amount of sand available in the admixture is shown in Figure 7b such that an exponential decrease in the detected values of m_v was observed while the sand weight proportion in the mixture increases. Similar to that α_v of, the distinct data points depict a very good agreement along with a continuous regression curve, which results in obtaining the relatively high value of R^2 = 0.9666, indicating that the investigated behavior is accurate and precise. The resulting behaviors (i.e., exponential decreases) observed for two important characteristics of consolidation compressibility properties point out that the consolidation deformational settlement exhibited in sandy soils employed in infrastructural applications can be reduced by including a greater amount of sand into the admixture soil fill in the field.

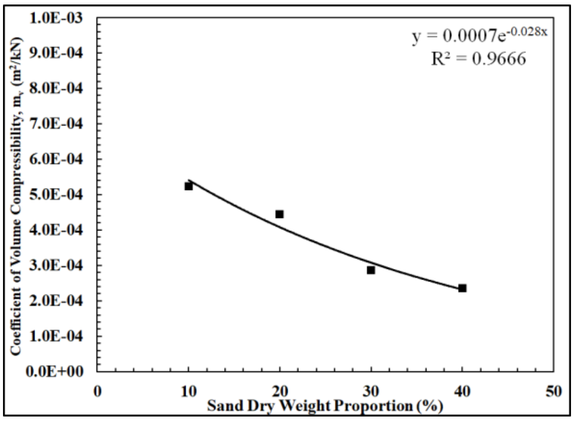
The variation of the coefficient of consolidation (c_v) (i.e., characterizing the rate and duration of consolidation settlement and deformation, respectively), as well as the coefficient of permeability [hydraulic conductivity] (i.e., identifying hydraulic properties) depending on the sand content, is shown in Figures 7c and 7d, respectively. The coefficient of permeability (k) based on the coefficient of consolidation (c_v) was calculated by following Terzaghi's one-dimensional consolidation theory. Since consolidation settlement of soil is a time-dependent process that depends on the hydraulic conductivity and the drainage conditions. The c_v governing the rate and speed of consolidation settlement for infrastructural soil fills in the field as well as the k controlling the drainage and expulsion of excess pore-water pressure from void space, resulting in the increase of vertical effective stress within the soil body against forces and stresses in order to provide larger bearing capacity under loading conditions are two critical and crucial engineering design properties to help us further understand consolidation characteristics and hydraulic properties of sandy clay soil fills in the geotechnical infrastructural applications. To this end, the variation of c_v and k concerning an increase in sand content of the admixture soil are shown in Figures 7c and 7d, respectively.

It can be observed that the coefficient of consolidation (c_v) (Figure 7c) increased, whereas the compression index (Figure 6c) decreased in the admixture test specimens with increased sand content. This reveals that the consolidation rate increases when coarse grain material (i.e., sand) increases in those admixture samples. Accordingly, the increase in sand weight proportion of sandy clay soil displayed an increase in the detected values of c_v with a decreasing rate at greater sand contents particularly above 30% up to 40% sand fraction by dry weight in the mixture. This depicts a behavior consisting of a power model for the measured and determined values of c_v as a function of increasing sand content in the admixture soil. The proximity obtained between distinct data points and the continuous regression curve of the power model remarks the relatively good agreement between the individual data points experimentally measured and defined and the power model curve analytically developed and generated.

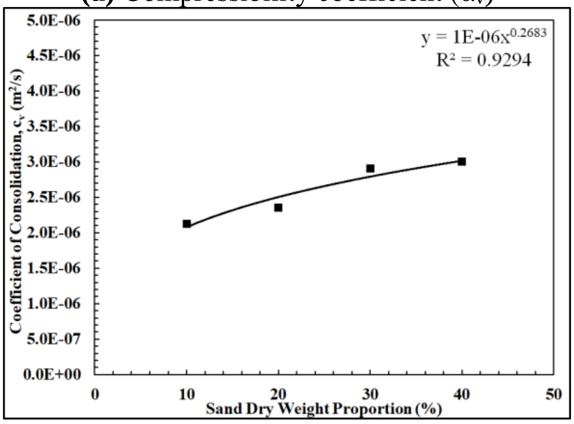
Additionally, the proximity attained results in acquiring a relatively high value of R^2 = 0.9294, which indicates the accuracy and precision of statistical analysis to unveil the behavior investigated due to the laboratory testing program for the change in c_v with an increase in sand content. Consequently, this extends the understanding of the increment in the rate of consolidation deformation with increasing sand mass proportion in sandy clays such that the consolidation settlement will ease, speed up, and accelerate owing to greater sand proportion in the admixture soil fill in the field. This could be advantageous for achieving settlement process under loading, force and stresses within relatively short time duration in soil fills employed in geotechnical infrastructures so that the soil fill will possess a larger bearing capacity facilitating higher strength and resistance against forces and stresses mobilizing within infrastructural fill. Further, it was investigated that the coefficient of permeability (k) increased as the amount of coarse-grained soil (i.e., sand) increased in the mixture. As such, an exponential increase (R^2 = 0.9770) in the values of k with increasing sand content is exhibited, as shown in Figure 7d. This is attributed to the improved hydraulic conductivity properties of sand when included in clayey soil to facilitate the enhanced drainage of excess pore-water pressure - built up due to external loads and forces exerted to infrastructural fill - from clayey soil owing to the inclusion of more and more sand amount into the admixture soil particularly above 30% up to 40% by dry mass proportion of sand. This will ease and expedite the progression of consolidation deformation. Hence, long-term settlement is accomplished within a relatively short period in soil fills designed and constructed by utilizing sandy clays in the infrastructural applications to reach higher bearing capacities quickly. Further, the computed values of α_v, m_v, c_v, and k at different sand contents (i.e., dry weight proportions) are tabulated in Table 6.



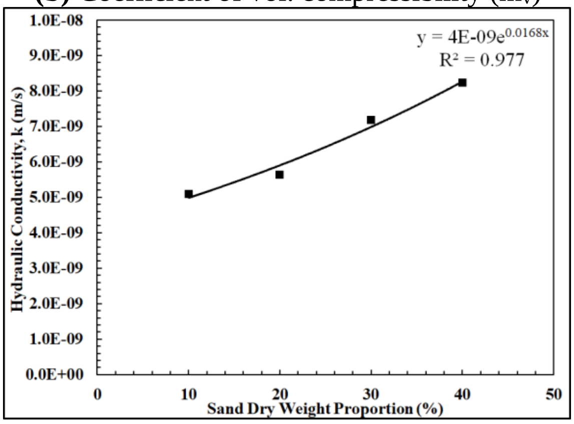
(a) Compressibility coefficient (α_v)



(b) Coefficient of vol. compressibility (m_v)



(c) Coefficient of consolidation (c_v)



(d) Hydraulic conductivity (k)

Figure 7. The variation in consolidation characteristics and hydraulic properties of sand-clay mixtures per sand content: statistical analysis on the investigated behavior

Table 6. The computed values of α_v, m_v, c_v, and k at different sand contents

Sand Content (%)	α_v (m²/kN)	m_v (m²/kN)	c_v (m²/s)	k (m/s)
10	0.00475	0.00052	2.1243×10^{-6}	5.09×10^{-9}
20	0.00399	0.00044	2.3552×10^{-6}	5.64×10^{-9}
30	0.00247	0.00029	2.9092×10^{-6}	7.19×10^{-9}
40	0.00203	0.00024	3.0074×10^{-6}	8.23×10^{-9}

The compressibility coefficient (α_v) and the coefficient of volume compressibility (m_v) decreased by 65% and 60%, respectively, owing to the inclusion of sand up to 40% by dry weight. Moreover, the coefficient of consolidation (c_v) and the hydraulic conductivity (k) increased by 55% and 75%, respectively, due to the addition of sand up to 40% by dry weight into the clayey soil.

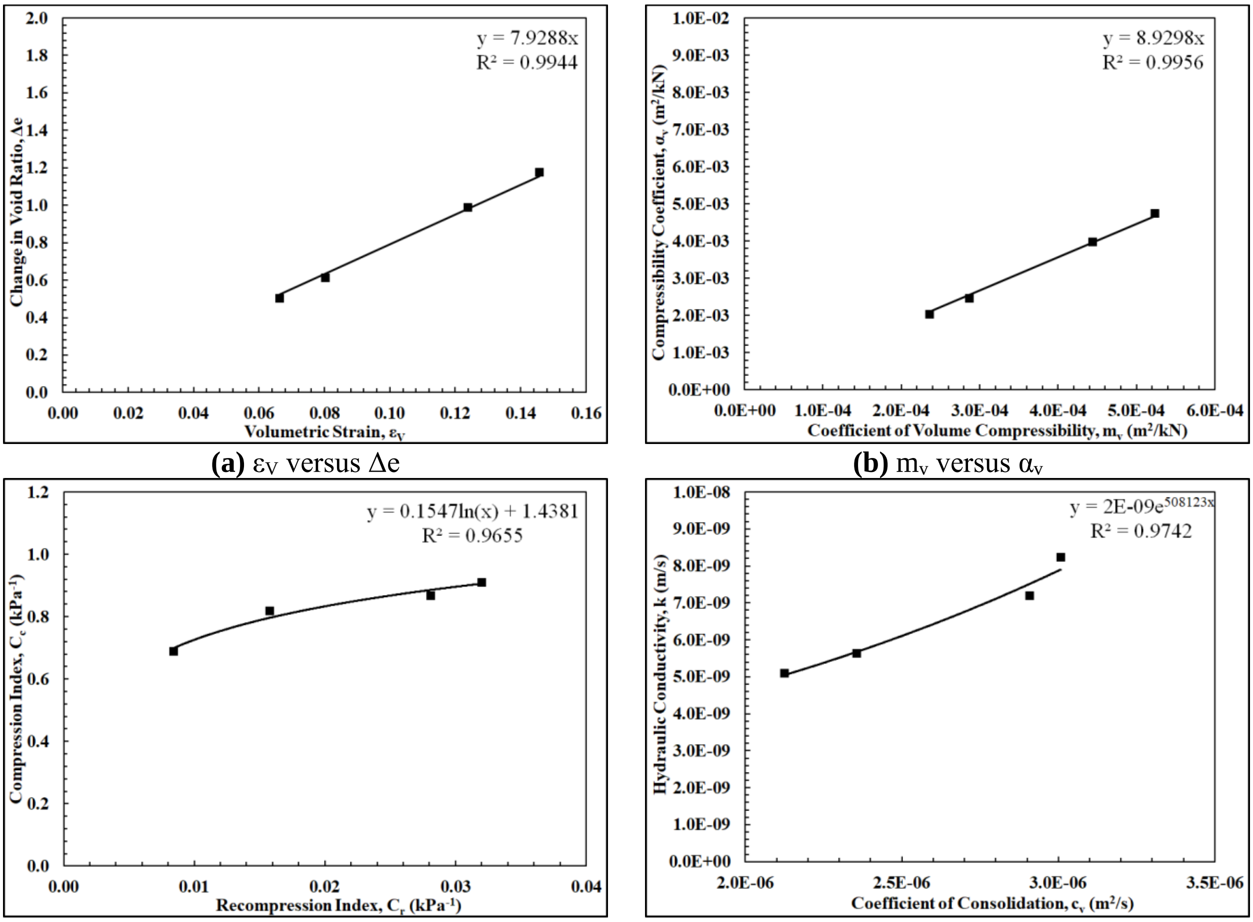
To sum up, the amount of vertical deformation detected governs the degree of consolidation settlement and, thus, is related to the magnitude of displacement measured in the vertical direction in the specimen. The vertical displacement measured in the specimens increased with increasing normal load. In contrast, it decreased with increasing sand content owing to the larger inherent strength characteristics of sand particles compared to weak and sensitive clay minerals. Therefore, it is further noted that the compressibility properties of clayey soil have been improved by including sandy soil that exhibits smaller vertical deformation under the same loading conditions. Regardless of loading conditions, either low, medium, or high, the magnitude of vertical displacement has reduced with an increase in sand content.

Further, it was seen that the decrease in void ratio resulted from incremental pressure - that could be related to the volumetric strain mobilized under loading reduced owing to the increasing sand content in clayey soil, thus enabling relatively greater bearing resistance against loading as well as providing higher strength response. This is attributed to the micro-inherent characteristics of admixtures such that relatively improved graded grain distribution of sandy clays as compared to pure clays containing one predominant soil mineral size facilitates the re-orientation of sand-particles and clay minerals for the ease and reformed re-organization of admixture micro-structure. In this way, the relatively denser soil is obtained with increasing sand proportion, resulting in less decrease in void ratio under identical pressure increment which controls the degree and severity of consolidation settlement through the volumetric strain displayed under loading in the field. Additionally, the increase in mass proportion of relatively rigid sand particles compared to weak, powerless clay minerals in the admixture enhances the sandy clays' overall bearing capacity, including greater sand contents. Further, analogous test results of laboratory experimental programs were likewise published by Iravanian and Bilsel [3], Mishra et al. [7], and Dutta and Mishra [8] for consolidation compressibility properties of sand-clay admixture soils in terms of extensive comparative analysis carried out to examine the changes in C_c, C_r, αv, m_v as a result of the increase or decrease in sand weight proportion in the fine-grained cohesive soils such as bentonite clay. Furthermore, similar research findings were also revealed by Chalermyanont and Arrykul [1], Gleason et al. [4], Kockar et al. [5], and Robinson and Allam [9] for hydraulic characteristics of sand-clay admixtures in terms of comprehensive analysis conducted to observe the variations in c_v, k owing to the change in sand content in the fine-grained cohesive soils including bentonite.

6. Comparative Analysis of Correlation Behavior of Engineering Properties

Further comparative analyses have been carried out to investigate correlation and the resulting behavior among distinct consolidation characteristics and hydraulic properties detected and determined due to the testing program conducted on sandy clays, including various sand contents ranging from 10% to 40%. The developed correlation models between various engineering design parameters to comparatively reveal the behavioral relationship are presented in Figure 8. It was obtained a linear relationship between the change in void ratio (Δe) and the volumetric strain (ε_V) with a very high value of coefficient of determination (R^2= 0.9944) (Figure 8a). The ε_V is linearly related to Δe through the initial volume of the soil. This was realized and confirmed due to a laboratory testing program in which consolidation tests were performed on sandy clays containing different sand contents. Likewise, a linear correlation was displayed between the compressibility coefficient (α_v) and the coefficient of volume compressibility (m_v) by showing a very high value of R^2 = 0.9956 (Figure 8b). Similarly, m_v is linearly interrelated to α_v through the initial volume of the soil. This was again attained and verified from the results of the testing program.

Figure 8c shows the relation between two important compressibility engineering design parameters: the compression index (C_c) and the recompression index (C_r). The mathematical model obtained as a result of statistical analysis is in the form of a natural logarithmic relationship with a relatively very high value of R2 = 0.9655 such that the rate of increase in Cc gets smaller than that of C_r. This specifies that although there was a gradual decrease in the detected values of both C_c and C_r with an increase in sand content up to 20%, a sharp decline commenced to be exhibited for the observed values of both C_c and C_r for the sand contents, particularly above 20%. Additionally, even though the amount of reduction displayed in the values of C_r was 70% with increasing sand content up to 40%, only a 25% reduction was seen in the values of $C_{c,}$ indicating that the inclusion of sand into clays benefits comparatively more the clayey soils under reconsolidation pressures by relatively greater improving their compressibility characteristics in providing larger strength response, and hence, greater bearing capacity against loading.



(a) ε_V versus Δe **(b)** m_v versus α_v

(c) C_r versus C_c **(d)** c_v versus k

Figure 8. Correlation behavior between engineering design parameters to comparatively investigate consolidation and hydraulic conductivity characteristics

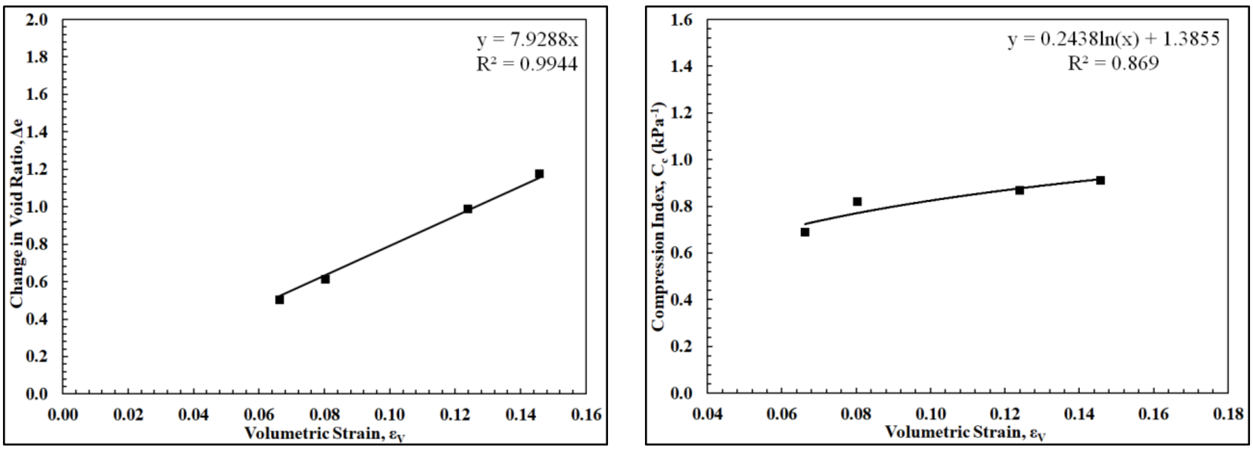
A statistical analysis has been conducted to analyze the variation in hydraulic conductivity properties (k) concerning the time rate of consolidation response (cv - a characteristic utilized engineering design parameter), such that the correlation behavior between k and c_v is presented in Figure 8d. The values of k increase exponentially as a function of c_v with an attained very high value of $R^2 = 0.9742$, which points out that although the inclusion of sand into clay up to 20% - 30% augments the hydraulic conductivity as progressively increasing manner, subsequently beyond 30% up to 40% sand content, the rate of increment becomes greater that the further addition of sand enhances the hydraulic conductivity as sharply increasing fashion owing to superior conductivity characteristics of sand. This ensures a relatively improved time rate of consolidation response as a result of accelerated expulsion (i.e., escape) of excess pore-water pressure and, thus, speedy (i.e., fast) consolidation deformation mobilized due to loads, forces, or stresses. Thereby, rapid and quick settlement progressed within soil fill-in infrastructural applications to expedite construction activities by shortening the overall duration of building. To sum up, as explicitly seen in Figures 8a through 8d, the proximity gained between the distinct data points and the continuous regression curves of analytical models developed from further statistical analysis specifies and remarks very good agreement, validity investigated in the developed correlation behavior between both consolidations as well as hydraulic conductivity engineering design parameters.

The degree of volumetric strain (ε_V) experienced by the soil during consolidation deformation because of load application, external forces, or internal stresses is important to clearly understand and deeply figure out the settlement mechanism initiating, mobilizing, and advancing extended. To this end, the change in consolidation engineering design characteristic parameters such as Δe, C_c, α_v, m_v, and c_v with the severity and concerning the magnitude of volumetric strain (ε_V) the sandy clayey soil has undergone is presented in Figure 9. As seen in Figure 9a, the variation in void ratio with a change in volumetric strain (ε_V) is indirectly relevant fashion such that a linear relationship having a zero intercept in both x and y axes with a very high value of $R^2 = 0.9944$

exhibited as a result of statistical analysis. This demonstrates that the results of the experimental findings achieve and ratify the consolidation theory such that the Δe is directly proportional to the ε_V through a constant being the initial volume of the soil for the sandy clay admixtures containing various sand contents ranging from 10% up to 40%. Moreover, the alteration in compression index (C_c) as a function of the change in volumetric strain (ε_V) is given in Figure 9b. The behavior based on statistical analysis displays a mathematical model of natural logarithmic variation with a good value of $R^2 = 0.8690$, indicating that the rate of increment in the measured and determined value of C_c decreases with the increasing value of ε_V. This points out that even though the amount of volumetric strain increases considerably, particularly for the sandy clay soils, including less and less sand content, especially below 20%, the degree and the magnitude of compressibility based on C_c increases only marginally to a slight extent. This moderate increase to a limited extent/degree is attributed to the clayey soil's inherent characteristics that depend on the repulsive and attractive forces based on physicochemical factors.

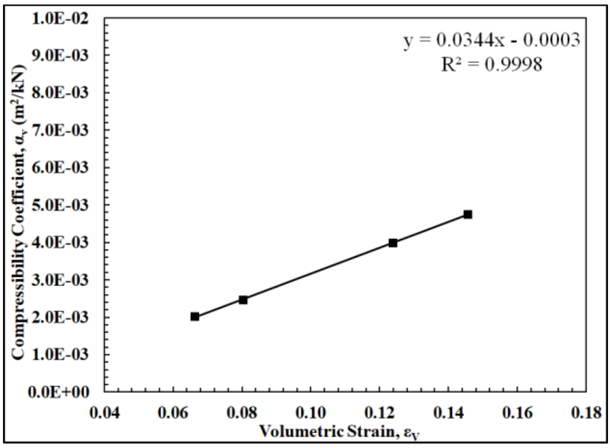
Furthermore, the compressibility coefficient (α_V) increases linearly with increasing volumetric strain (ε_V) (Figure 9c), as confirmed by the analytical model (with an excellent $R^2 = 0.9998$) developed per the further statistical analysis performed on the experimental data. This was anticipated that the α_V directly related to Δe due to the intensity of stress increase (Δσ′) within the soil is directly proportional to ε_V the soil has undergone due to the severity of loading and imposed forces. Hence, the magnitude of α_V changes linearly concerning the increased degree of ε_V. The sandy, clayey soil has been subjected to a lack of sufficient sand content, particularly for low sand amounts (i.e., 10%).

Lastly, Figure 9d presents the inversely proportional nonlinear (i.e., exponential) relationship between the coefficient of consolidation (c_v) and the volumetric strain (ε_V). The statistical analysis results provided an excellent R2 = 0.9944, demonstrating that there is very good agreement and proximity among distinct data points and continuous regression behavior curve. This is concerned with the observed characteristics of sandy clay soil mixtures. The increase in sand content leads to the reduced volumetric strain experienced by the sand-clay mixture becoming relatively larger resistant against loads and, hence, possessing greater bearing capacity under induced forces or stresses. Therefore, this is also relevant to the improvement of the consolidation properties, and thus, the enhancement of the time rate of consolidation (i.e., c_v) leading to the moderate expulsion of excess pressure and the accelerated escape of excess pore-water as a result of having higher hydraulic conductivity features owing to the increment in c_v and hence, the increase in k at greater sand contents in sandy, clayey soil. To sum up, the consolidation parameters, including Δe, C_c, α_v have depicted directly proportional behavior, whereas the c_v has shown inversely proportional response as a function of volumetric strain (ε_v).

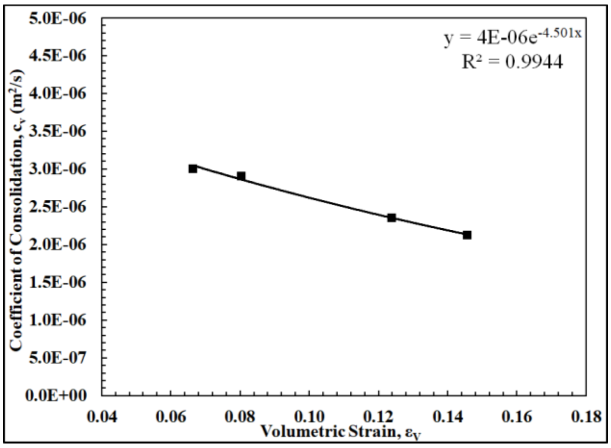


(a) Δe versus ε_V **(b)** C_c versus ε_V

Figure 9. Variation of consolidation engineering design properties with the degree of volumetric strain (ε_v) sand-clay mixture experienced



(c) α_v versus ε_V

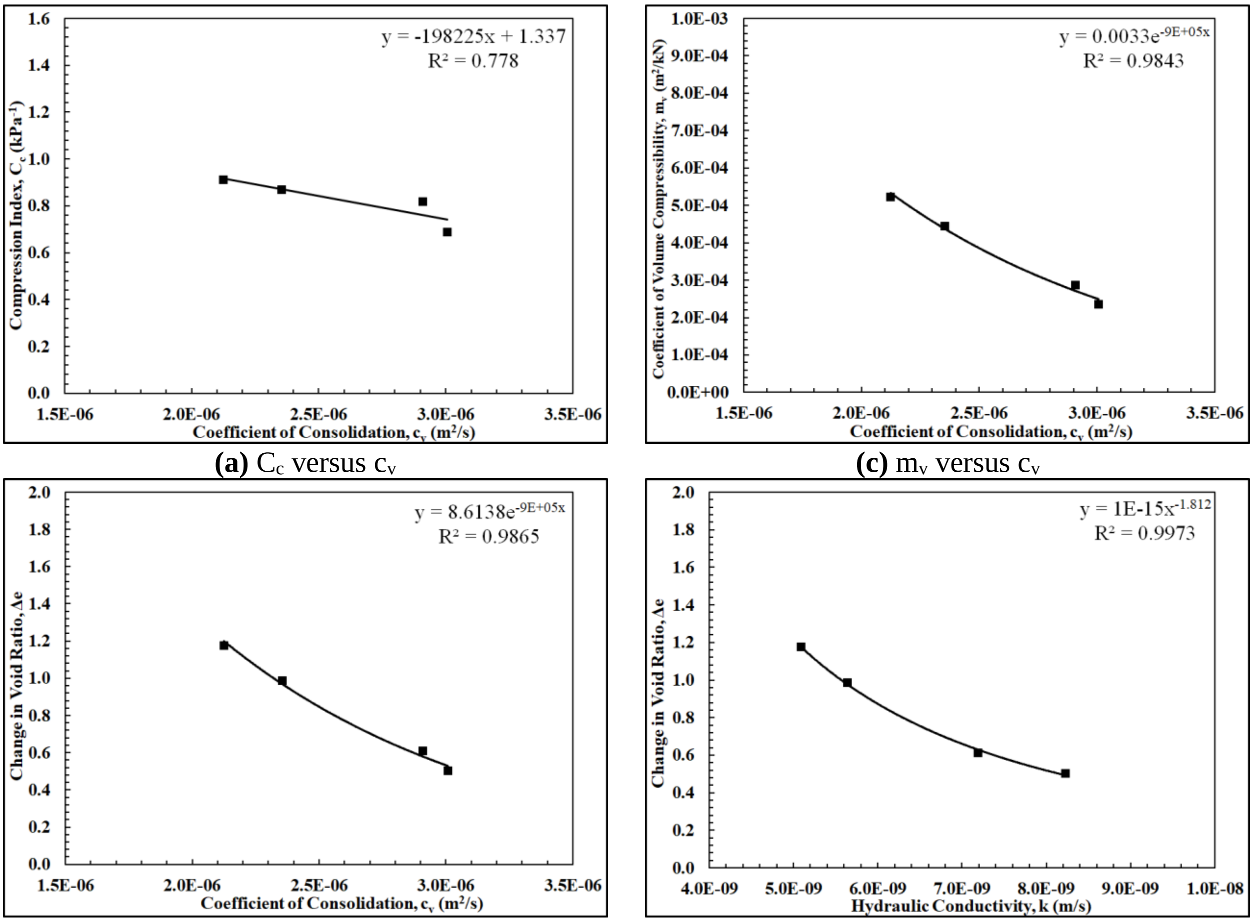


(d) c_v versus ε_V

Figure 9. (Continued) Variation of consolidation engineering design properties with the degree of volumetric strain (ε_v) sand-clay mixture experienced

The relationship based on the relativeness of consolidation engineering design properties and the resulting developed mathematical models for the detected behavior according to the performed statistical analysis is presented in Figure 10. The alteration of an important compressibility design parameter (i.e., C_c) governing the magnitude of final consolidation settlement concerning the change in the rate of consolidation engineering property (i.e., c_v) controlling the speed and progression of consolidation deformation is shown in Figure 10a. It was obtained that the C_c decreases while the c_v increases, indicating that an inverse correlational behavior with an inversely linear model between C_c and c_v is exhibited. This specifies that the amount of decrease in C_c is relevant and comparatively proportional to the amount of increase in c_v owing to the additional inclusion of sand into sandy, clayey soil by further increasing sand content so that the admixture soil will undergo lower consolidation settlement per having relatively higher bearing capacity/resistance properties against loading as well as will possess improved and superior characteristics in allowing the quick escape of pore-water, and thereby, rapid reduction and decay of excess pore pressure so as that the time rate for the continued consolidation deformation is sped up and accelerated that could be towards the benefit and advantage of construction activities of soil fills composed of sandy clays in the field.

The correlative relationship between the coefficient of volume compressibility (m_v) (i.e., governing compressibility characteristics) and coefficient of consolidation (c_v) (i.e., controlling the rate/speed of consolidation) is displayed in Figure 10b such that an exponential behavior with an attained high value of $R^2 = 0.9843$ was obtained. As such, the rate of decline in the measured and determined value of m_v decreases with increasing the detected value of c_v. This is a consequence of sand inclusion into clayey soil that the rate/speed of consolidation rises substantially owing to relatively enhanced hydraulic properties of coarse-grained material (sand). At the same time, the reduction in magnitude of m_v is limited even though the sand fraction in the mixture is further increased above 20% by dry weight. However, the improvement in compressibility properties is considerable, such that the decrease in the m_v is important. This shows and remarks that the load resistance capability of clayey soil is boosted by the addition of sand, providing that the degree and the amount of the resulting consolidation deformation progressed in soil under loads/forces, stresses diminish, aiding in accomplishing smaller extent and magnitude of consolidation settlement mobilized and observed in the field for the infrastructural applications constructed by utilizing sandy clays.



(a) C_c versus c_v **(c)** m_v versus c_v

(b) Δe versus c_v **(d)** Δe versus k

Figure 10. Relativeness of consolidation engineering design parameters and the resulting mathematical model for the behavior based on statistical analysis

The relativeness and the mathematical model between two important consolidation properties, change in the void ratio (Δe) and coefficient of consolidation (c_v), are presented in Figure 10c. There occurs an exponential decline in the measured values of Δe with increasing detected values of c_v such that the analytical model developed as a result of statistical analysis provided a very high $R^2 = 0.9865$ value. This shows a very good proximity among distinct experimentally attained data points and a statistically developed model. Under load application, the void ratio reduction becomes smaller owing to sand inclusion. As known, the resulting magnitude of consolidation settlement experienced in the field for the soils subjected to loads, forces, and stresses is governed by the degree of reduction in void ratio. As such, fine-grained soils (pure clays) generally exhibit much larger changes in void ratio when exposed to loads. However, the inclusion of sand into clay benefits not only the increment for the consolidation rate (c_V) for facilitating accelerated consolidation but also the diminish generated for the void ratio (Δe) so that the sandy soil has become relatively stronger by possessing greater strength and bearing capacity. Finally, the variation between the change in void ratio (Δe) and the coefficient of permeability (k) is given in Figure 10d. An inverse power model with an excellent $R^2 = 0.9973$ was investigated such that the Δe decays nonlinearly with an increase in k due to sand inclusion into clay, which improves hydraulic conductivity properties and enhances strength characteristics under loads. The resulting observed behavior between Δe and k eventually specifies that sandy soils' consolidation characteristics and hydraulic properties are intensified and rehabilitated, respectively. Consequently, the soil fills designed and constructed utilizing sand-clay mixtures in geotechnical infrastructural applications will become robust and durable due to sand inclusion during construction.

7. Conclusion

The resulting consolidation behaviors and compression responses detected by means of the most important characteristics of consolidation compressibility properties, including C_c, C_r, α_v, m_v, Δe, and ε_V pointed out that the consolidation deformational settlement exhibited in sandy soils employed in infrastructural applications can be reduced by inclusion of greater amount of sand into the admixture soil fill in the field. Furthermore, the variation of the coefficient of consolidation (c_v) (i.e., characterizing the rate and duration of consolidation settlement and deformation, respectively) as well as the coefficient of permeability (k) [hydraulic conductivity] (i.e., identifying hydraulic properties) depending on the sand content showed that the coefficient of consolidation (c_v) increased whereas the compression index decreased in the admixture test specimens with increased sand content. This reveals that the consolidation rate increases when coarse grain material (i.e., sand) increases in those admixture samples. Accordingly, the increase in sand weight proportion of sandy clay soil displayed an increase in the detected values of c_v with a decreasing rate at greater sand contents particularly above 30% up to 40% sand fraction by dry weight in the mixture. Consequently, this extends the understanding of the increment in the rate of consolidation deformation with increasing sand mass proportion in sandy clays such that the consolidation settlement will ease, speed up, and accelerate owing to greater sand proportion in the admixture soil fill in the field. This could be advantageous for achieving settlement process under loading, force and stresses within relatively short time duration in soil fills employed in geotechnical infrastructures so that the soil fill will possess a larger bearing capacity facilitating higher strength and resistance against forces and stresses mobilizing within infrastructural fill. It was also investigated that the coefficient of permeability (k) increased as the amount of coarse-grained soil (i.e., sand) increased in the mixture. This is attributed to the improved hydraulic conductivity properties of sand when included in clayey soil to facilitate the enhanced drainage of excess pore-water pressure - built up due to external loads and forces exerted to infrastructural fill - from clayey soil owing to the inclusion of more and more sand amount into the admixture soil particularly above 30% up to 40% by dry mass proportion of sand. This will ease and expedite the progression of consolidation deformation. Hence, long-term settlement is accomplished within a relatively short period in soil fills designed and constructed by utilizing sandy clays in the infrastructural applications to reach higher bearing capacities in a short time interval.

To conclude, in projects where sandy clay soil fills are designed and constructed, in addition to the size (i.e., magnitude) and severity of possible settlements, the speed (i.e., rate) of the deformation to occur and its progress development over time are also crucial for the performance and service life of geotechnical infrastructural projects. To this end, the different ratios of sand additives, the variation in the related consolidation engineering parameters, and the change in the dependent hydraulic properties were comprehensively studied and investigated in this research study consisting of a wide-spectrum laboratory testing program. Besides, several different contrary factors work in the opposite direction, resulting in reverse effects for the mobilization as well as progression and continuation of consolidation settlement, primarily plastic deformation. In this regard, the higher the hydraulic conductivity in the 40% sand mixture, the shorter the time duration to allow the pore-water to leave/escape out of the body of soil mixture (i.e., the expulsion of excess pore-water to subside high pressure developed within the soil as a result of loading) which triggers and initiates the rapid development of consolidation settlement through the progress and advancement of quick short-term sudden deformation that is in immediate elastic mode resulting in the improvement of rate as well as the enhancement of speed of consolidation displacement being in long-term permanent plastic mode. In this way, the characteristics of consolidation behavior change and evolve from predominantly/mainly irreversible long-term plastic nature of settlement to principally elastoplastic type exhibiting considerable reversible short-term elastic form of deformation (i.e., vertical displacement).

Further, rapid and speedy deformation is generally a consequence of elastic behavior and can be directly related to the stiffness of the soil. The sample including 40% sand has a stiffer and relatively rigid micro-, meso-, and macro-structure compared to the sample containing 10% sand. To sum up, the stiffness of coarser and harder solid sand particles is much higher as compared to very small and weak, sensitive clay particles of microscopic size, and as its ratio in the mixture increases, it shows greater strength and resistance against consolidation loading which displays an effect and demonstrates a role in minimizing the occurrence of large extent of deformation, and hence, the progression of great extent of settlement.

Author Contributions

The first author directed the project and supervised this study's findings. The first and the second authors devised the main conceptual ideas and developed the theoretical framework. The second author performed the experiments, and the first author conducted the statistical analyses. The first author wrote the manuscript. All authors read and approved the final version of the paper.

Conflicts of Interest

All the authors declare no conflict of interest.

Ethical Review and Approval

No approval from the Board of Ethics is required.

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